Results on Triboson production and limits on aQGC from the LHC

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Outline

- Introduction
- SM analysis
- aQGC search
- Conclusions

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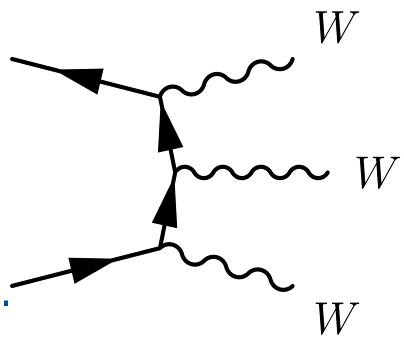
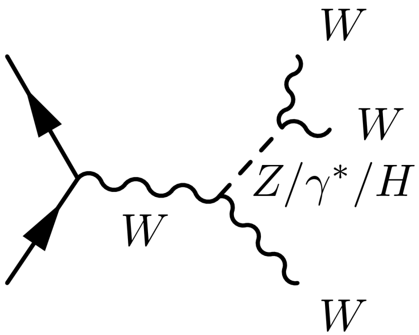
Introduction

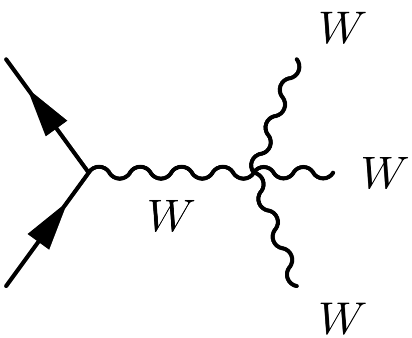
- For the first time sensitive to triboson production at hadron colliders!
  - First experimental evidences achieved already!
  - Important test of the Electroweak sector.
  - Potential for evidence of Quartic Gauge Coupling (QGC).
    - Not observed yet!
    - Complementary to VBS analyses.



- Important to constrain these processes from data.
  - Background to many direct new physics searches.
  - Connected to Higgs through VH.

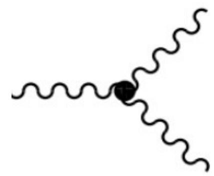


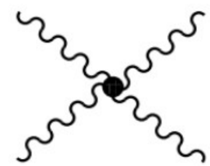
- Results used to search for new physics:
  - Parametrize result with Effective Field Theory (EFT) anomalous Quartic Gauge Coupling (aQGC) operators.



Intro: Why measuring tribosons processes? Test EWK theory!

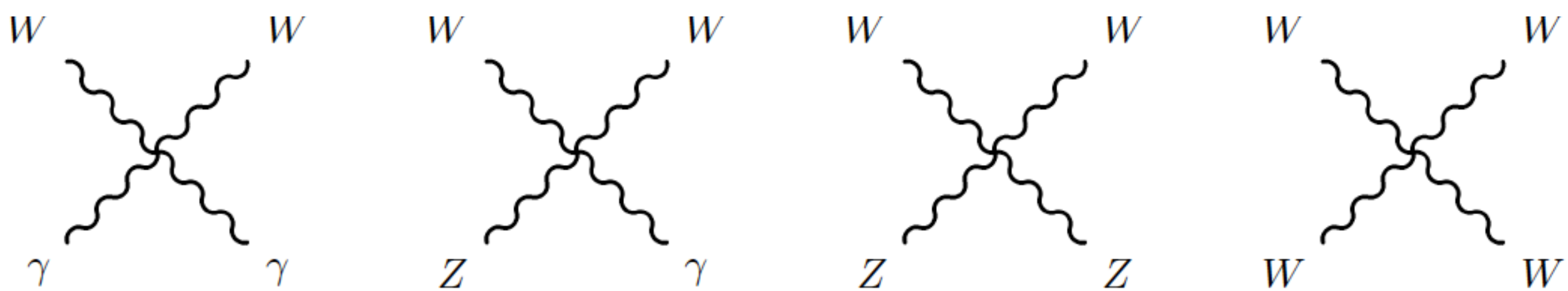
- Trilinear and Quartic Gauge boson couplings (TGC, QGC) are precisely determined by the non-Abelian nature of the SU(2) x U(1) gauge symmetry group that governs the Electroweak theory.
  - Neutral coupling forbidden.
  - TGC:
    - VBF and VV production.
  - QGC:
    - VBS and VVV production.





- The following Lagrangian contains all the authorized QGC in the SM:

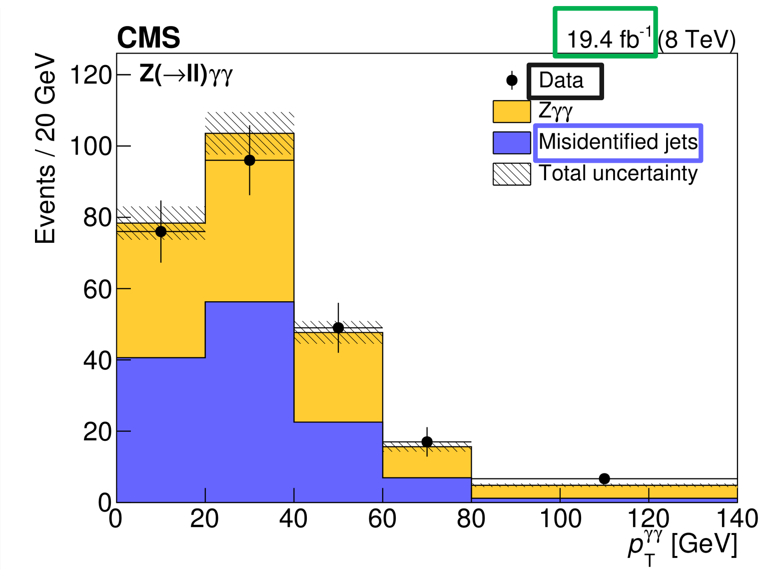
$$\mathscr{L}_{WWVV} = -\frac{g^2}{4}\Big\{[2W_\mu^+ W^{-\mu} + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)^2]^2 - [W_\mu^+ W_\nu^- + W_\nu^+ W_\mu^- + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)(A_\nu \sin\theta_W - Z_\nu \cos\theta_W)]^2\Big\}$$

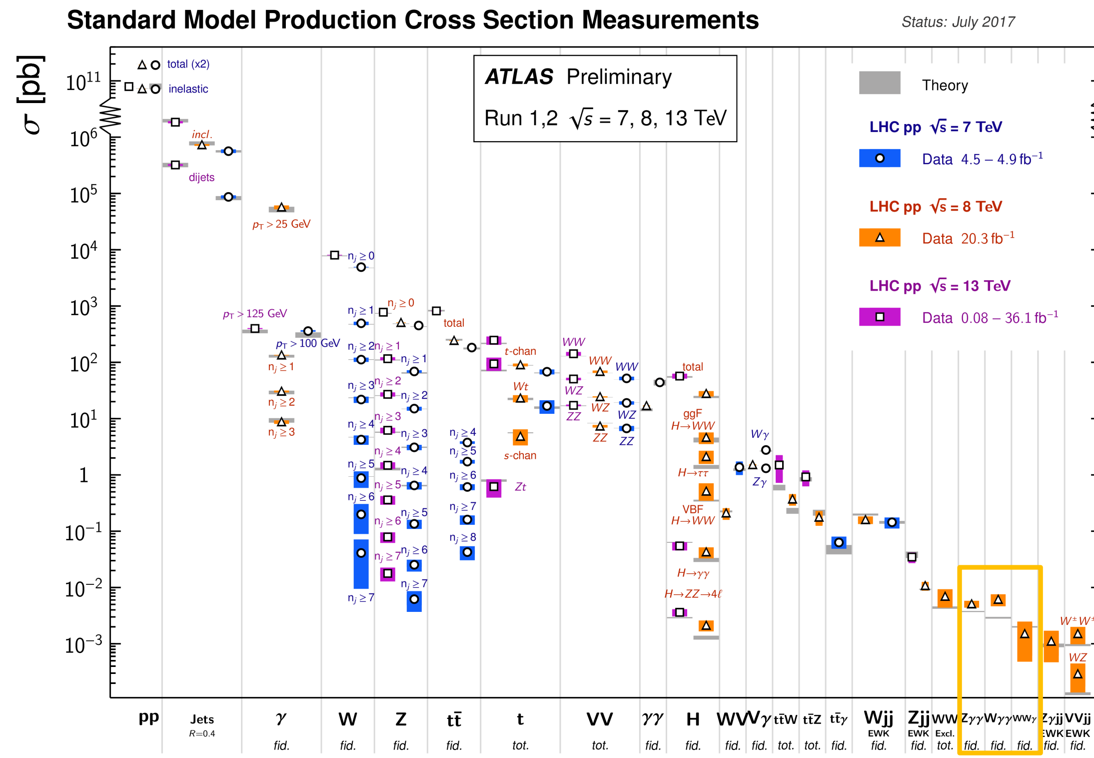


- A precise determination of the QGC in triboson final states allow to test the EW theory!

Intro: What do we measure?

CMS: arXiv:1704.00366 submitted to JHEP
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults





$$\sigma_{fid} = \frac{N_{data} - N_{bkg}}{lumi \times C}$$

$$\sigma_{tot} = \frac{N_{data} - N_{bkg}}{lumi \times A \times C}$$

Where:

- C is the efficiency correction due to the reconstruction (Nreco/Nfid).
- A is signal acceptance in the fiducial volume (Nfid/NTot).

Tribosons:
Some of the lowest cross-sections we can measure (σ_{fid}~fb or less)!

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W(→lν)γγ

ATLAS: Phys. Rev. Lett. 115, 031802 (2015)
CMS: arXiv:1704.00366 submitted to JHEP

- First experimental evidence (>3.σ) for triboson production at hadron collider reported by ATLAS in 2015!
- Fiducial definition:

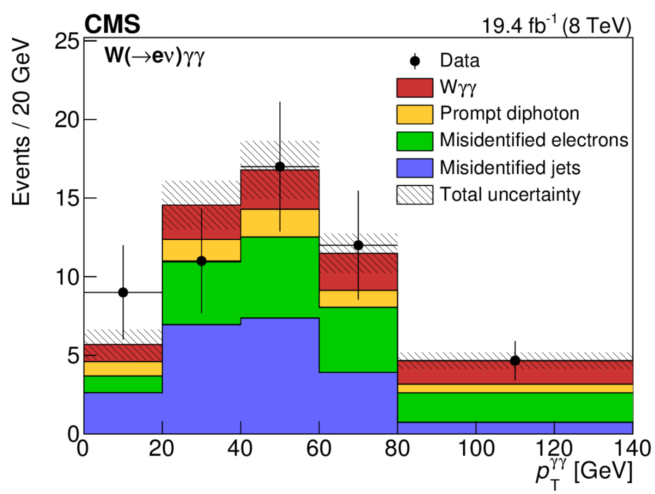
ATLAS:

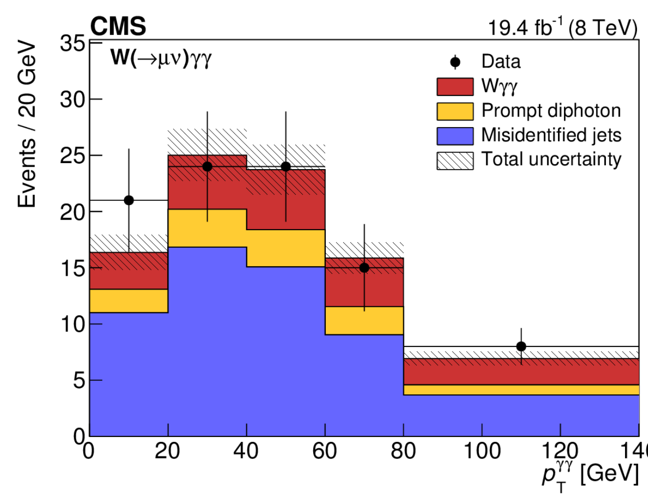
Definition of the fiducial region
$p_{\mathrm{T}}^{\ell} > 20\,GeV$, $p_{\mathrm{T}}^{\nu} > 25\,GeV$, $\lvert\eta_{\ell}\rvert < 2.5$
$m_{\mathrm{T}} > 40\,GeV$
$E_{\mathrm{T}}^{\gamma} > 20\,GeV$, $\lvert\eta^{\gamma}\rvert < 2.37$, iso. fraction $\epsilon_{\mathrm{h}}^{\mathrm{p}} < 0.5$
$\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\ell/\gamma,\mathrm{jet}) > 0.3$
Exclusive: no anti-k_t jets with $p_{\mathrm{T}}^{\mathrm{jet}} > 30\,GeV$, $\lvert\eta^{\mathrm{jet}}\rvert < 4.4$

CMS:

Definition of the $W\gamma\gamma$ fiducial region
$p_{\mathrm{T}}^{\gamma} > 25\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_{\mathrm{T}}^{\ell} > 25\,\mathrm{GeV}$, $\lvert\eta^{\ell}\rvert < 2.4$
One candidate lepton and two candidate photons
$m_{\mathrm{T}} > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$

- Backgrounds:
  - *W+jets and Wγ+jet (2D-template fit of isolation and Photon ID), γγ+jet estimated from data, Zγ scaled in CR.*





W(→lν)γγ

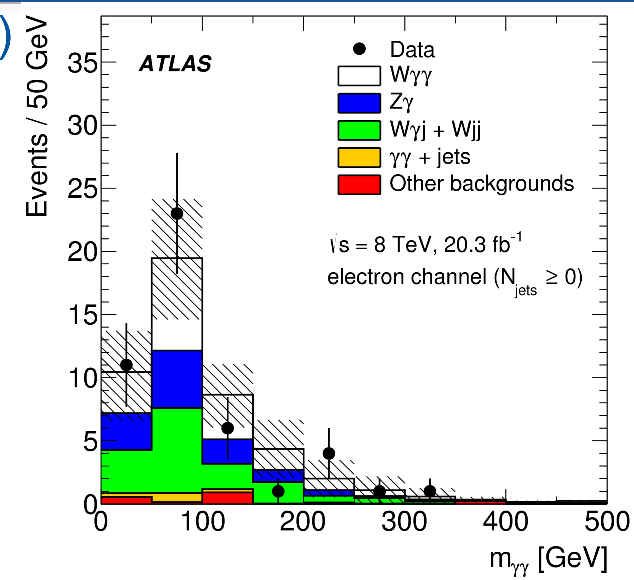
ATLAS: Phys. Rev. Lett. 115, 031802 (2015)
CMS: arXiv:1704.00366 submitted to JHEP

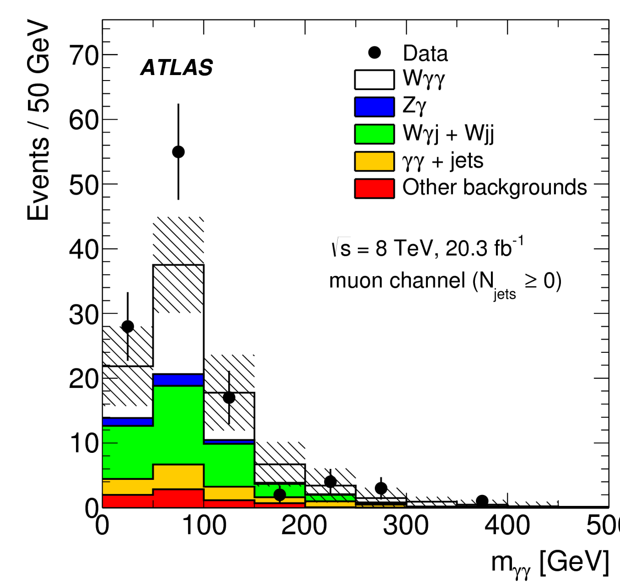
- ATLAS reported cross-section in both inclusive (≥0jets) and exclusive (=0jets) jets bins.
  - ~2.σ discrepancy with NLO prediction in inclusive measurement (1.σ exclusive).

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

- CMS reported cross-section in inclusive jet bins and found good agreement with predictions.

Channel	Measured fiducial cross section
$W\gamma\gamma \to e^{\pm}\nu\gamma\gamma$	$4.2 \pm 2.0\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$W\gamma\gamma \to \mu^{\pm}\nu\gamma\gamma$	$6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})$ fb
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	$4.9 \pm 1.4\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
Channel	**Prediction**
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	4.8 ± 0.5 fb





Z→(ll) ɣɣ

ATLAS: *Phys. Rev. D 93, 112002 (2016)*
CMS: arXiv:1704.00366 submitted to JHEP

- First experimental observation (>5σ) for triboson production at hadron collider reported by ATLAS in 2016!
- Fiducial definition:

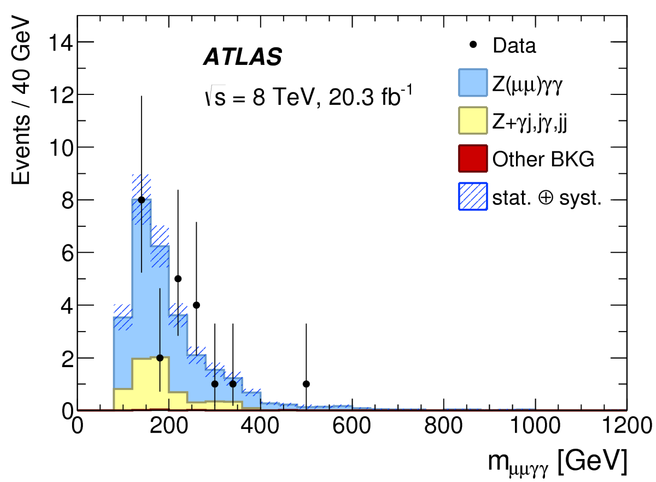
ATLAS:

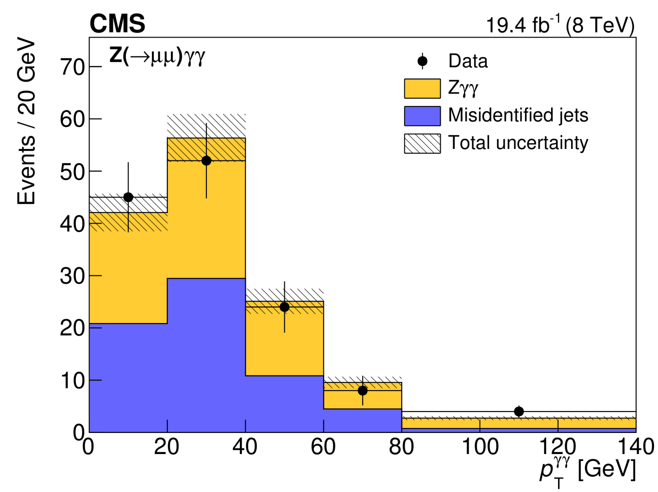
Cuts	$\ell^+\ell^-\gamma\gamma$
Lepton	$p_T^\ell > 25$ GeV
	$\lvert\eta^\ell\rvert < 2.47$
Boson	$m_{\ell^+\ell^-} > 40$ GeV
Photon	$E_T^\gamma > 15$ GeV
	$\lvert\eta^\gamma\rvert < 2.37$
	$\Delta R(\ell,\gamma) > 0.4$
	$\Delta R(\gamma,\gamma) > 0.4$
	$\epsilon_h^p < 0.5$
Jet	$p_T^{\rm jet} > 30$ GeV, $\lvert\eta^{\rm jet}\rvert < 4.5$
	$\Delta R(\text{jet},\ell/\gamma) > 0.3$ $\Delta R(\text{jet},\gamma) > 0.3$
	Inclusive : $N_{\rm jet} \geq 0$, Exclusive : $N_{\rm jet} = 0$

CMS:

Definition of the $Z\gamma\gamma$ fiducial region
$p_T^\gamma > 15\,\text{GeV}$, $\lvert\eta^\gamma\rvert < 2.5$
$p_T^\ell > 10\,\text{GeV}$, $\lvert\eta^\ell\rvert < 2.4$
Two oppositely charged candidate leptons and two candidate photons
leading $p_T^\ell > 20\,\text{GeV}$
$m_{\ell\ell} > 40\,\text{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$

- Backgrounds:
  - *Z+jets and Zɣ+jet (2D fit of isolation and Photon ID), other bkg negligible.*





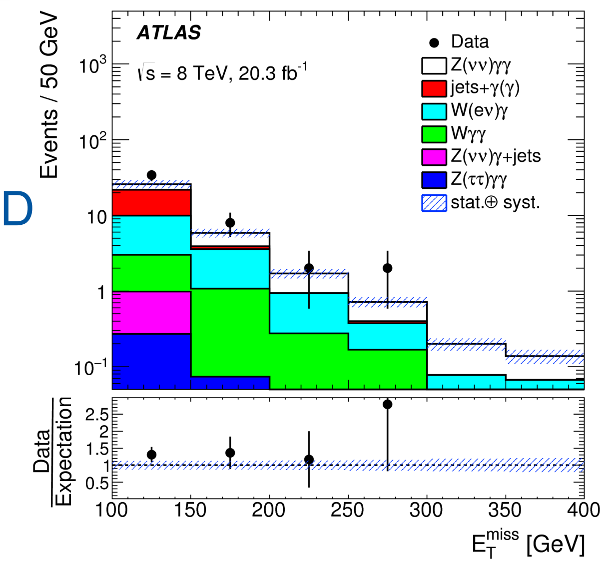
Z(→νν)γγ

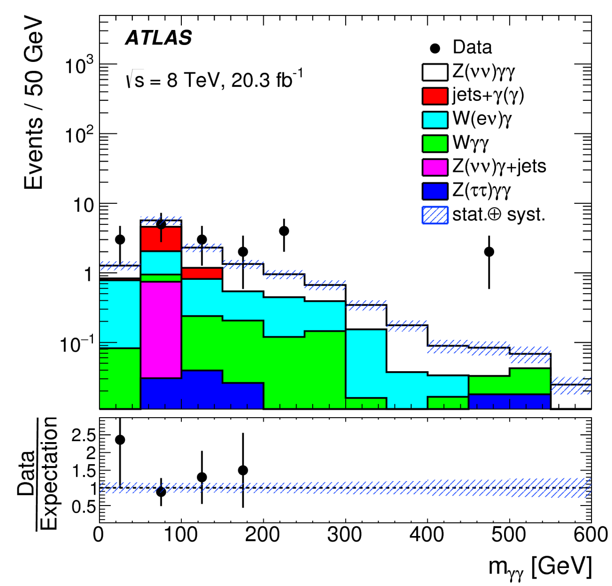
ATLAS: *Phys. Rev. D 93, 112002 (2016)*
CMS: arXiv:1704.00366 submitted to JHEP

- ATLAS also reported a search for Z(→νν)γγ production with a sensitivity to the SM process of about 1σ.
- Backgrounds:
  - Mismeasured jets in photons determined using ABCD method (ETMiss, Photon ID).
  - e→γ misID determined using fake rates from *Z→ee*
  - *W*γ scaled from data.
  - γ+jets from MC (Sherpa, checked in CR)
  - Other bkg determined from MC.
- Fiducial definition:

Cuts	$\nu\bar{\nu}\gamma\gamma$
Lepton	-
	-
Boson	$p_{\mathrm{T}}^{\nu\bar{\nu}} > 110$ GeV
Photon	$E_{\mathrm{T}}^{\gamma} > 22$ GeV
	-
	$\Delta R(\gamma,\gamma) > 0.4$
Jet	
	$\Delta R(\mathrm{jet},\gamma) > 0.3$

- Experimentally also add cut on: $\Delta\phi(p_T^{Miss},\gamma\gamma) > 5/6\pi$ to remove γ+jets





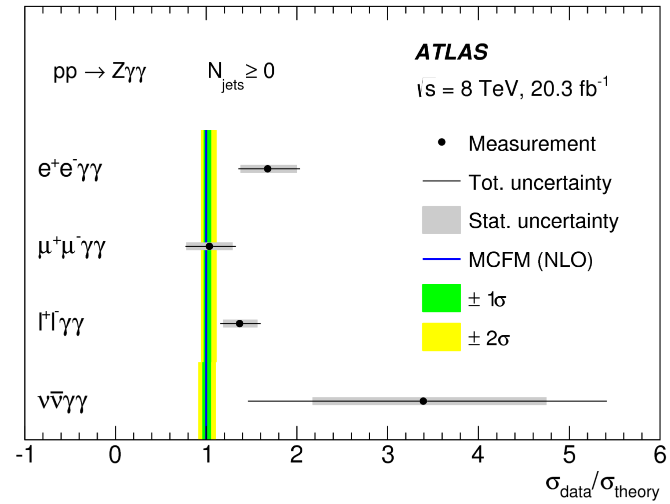
Zγγ results

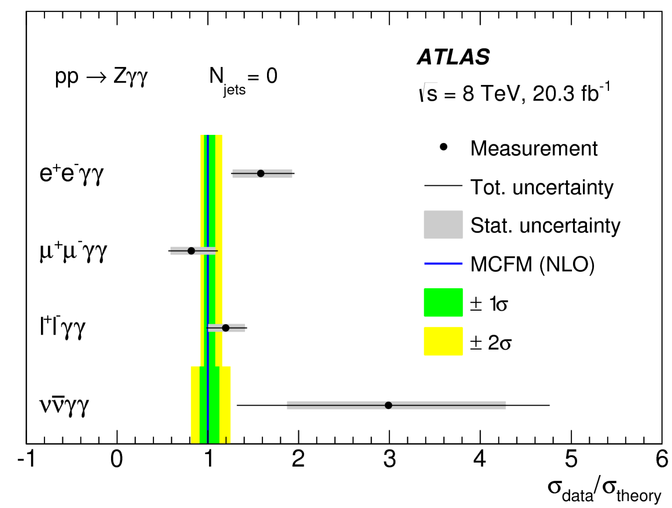
ATLAS: *Phys. Rev. D 93, 112002 (2016)*
CMS: arXiv:1704.00366 submitted to JHEP

- ATLAS reported cross-section in both inclusive (≥0jets) and exclusive (=0jets) jets bins.
  - Results are in ~agreement with NLO prediction in leptonic channel (although slightly above for the inclusive case).
  - In the neutrino channel an excess is observed but not really significant given the errors
- CMS reported cross-section in inclusive jet bins and found good agreement with predictions.

Channel	Measured fiducial cross section
$Z\gamma\gamma \to e^+e^-\gamma\gamma$	$12.5 \pm 2.1\,(\text{stat}) \pm 2.1\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \mu^+\mu^-\gamma\gamma$	$12.8 \pm 1.8\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \ell^+\ell^-\gamma\gamma$	$12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb

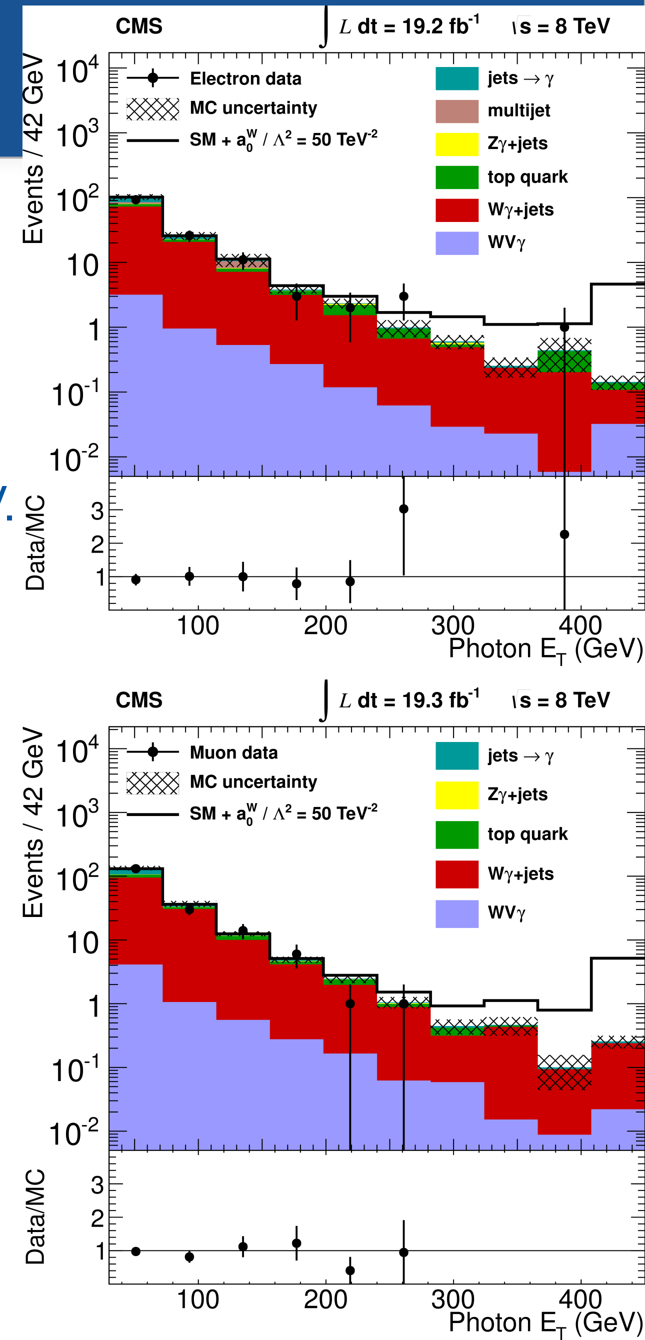
Channel	Prediction
$Z\gamma\gamma \to \ell^+\ell^-\gamma\gamma$	13.0 ± 1.5 fb





CMS W(→lν)V(→jj)γ

- First triboson analysis performed at the LHC.
- Selection:
  - 1 lepton (e,μ) with $p_T^e>30$ GeV or $p_T^\mu>25$ GeV.
  - 1 *γ with* $p_T^\gamma>30$ GeV.
  - At least 2 jets pT>30 GeV, no btag, $70<m_{jj}<100$ GeV.
  - $E_T^{Miss}>35$ GeV.
  - $m_T>30$ GeV
  - Z veto in electron channel.
- Backgrounds:
  - W*γ+jets:* sideband fit in m_{jj}.
  - Jets→γ extrapolated from data.
  - Jets→*l* fit To E_T^{Miss}.
  - Other bkg estimated for MC.
- Set 95% C.L. limits on cross section *σ*=311 fb.
  - Expected *σ*= (92±22) fb.



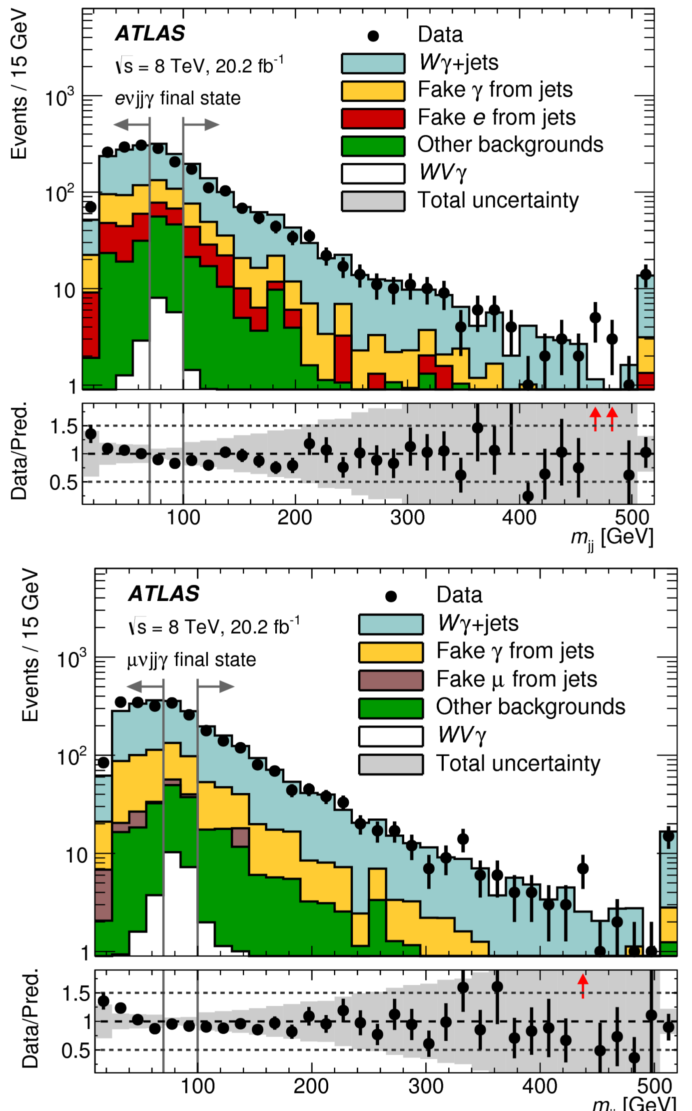
ATLAS W(→lν)V(→jj)ɣ

arXiv:1707.05597 submitted to EPJC

ATLAS performed this analysis: W(→lν)V(→jj)ɣ

Fiducial definition:

	$\ell\nu jj\gamma$
Leptons	1 electron or 1 muon $p_{\mathrm{T}} > 25$ GeV no 2$^{\mathrm{nd}}$ lepton ($p_{\mathrm{T}} > 7$ GeV) $\lvert\eta\rvert < 2.5$
Photon	≥ 1 isolated photon $E_{\mathrm{T}} > 15$ GeV isolation fraction $\epsilon_h^p < 0.5$ $\lvert\eta\rvert < 2.37$ $\Delta R(\ell, \gamma) > 0.5$
Jets	$N_{\mathrm{jets}} \geq 2$ and $N_{b\text{-jets}} = 0$ $p_{\mathrm{T}} > 25$ GeV $\lvert\eta\rvert < 2.5$ $\lvert\Delta\eta_{jj}\rvert < 1.2$ $\Delta R_{jj} < 3.0$ 70 GeV $< m_{jj} <$ 100 GeV $\Delta R(\mathrm{jet}, \gamma) > 0.5$ $\Delta R(\mathrm{jet}, \ell) > 0.3$
W boson	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $m_{\mathrm{T}} > 30$ GeV



Backgrounds:

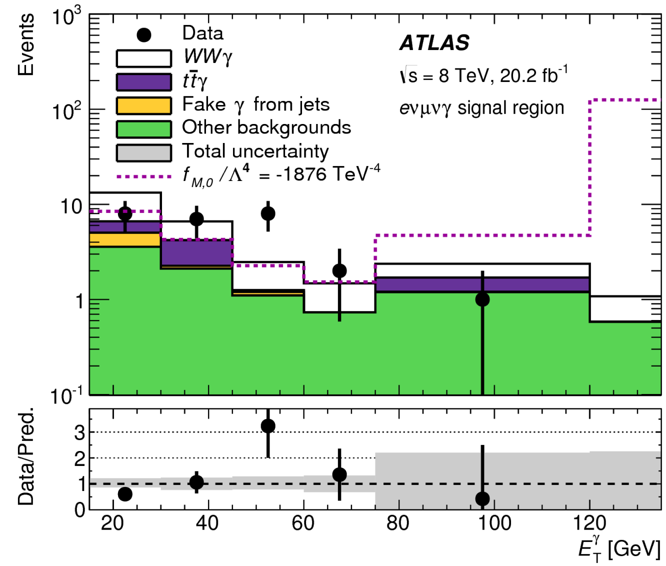
- W(→lν)V(→jj)ɣ *: Wɣ+jets,* fake j→ɣ, fake j→*e,* fake e→ɣ from simultaneous fit, rest MC.

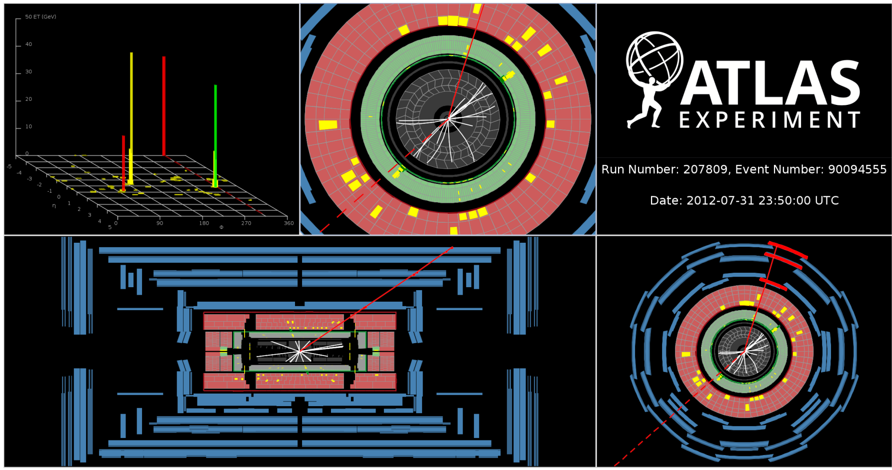
ATLAS W(→eν)W(→μν)ɣ

ATLAS also performed this analysis in the W(→eν)W(→μν)ɣ channels.

Fiducial definition:

	$e\nu\mu\nu\gamma$
Leptons	1 electron and 1 muon $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ no 3rd lepton ($p_{\mathrm{T}} > 7\,\mathrm{GeV}$) $\|\eta\| < 2.5$ opposite charge leptons $\Delta R(\ell, \ell') > 0.1$
Photon	≥ 1 isolated photon $E_{\mathrm{T}} > 15\,\mathrm{GeV}$ isolation fraction $\epsilon_h^p < 0.5$ $\|\eta\| < 2.37$ $\Delta R(\ell, \gamma) > 0.5$
Jets	$N_{\mathrm{jets}} = 0$ $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ $\|y\| < 4.4$ $\Delta R(\mathrm{jet}, \gamma) > 0.5$ $\Delta R(\mathrm{jet}, \ell) > 0.3$
W boson	$E_{\mathrm{T,rel}}^{\mathrm{miss}} > 15\,\mathrm{GeV}$ $m_{e\mu} > 50\,\mathrm{GeV}$





Backgrounds:

- W(→eν)W(→μν)ɣ: fake j→ɣ, fake j→*e*, fake e→ɣ from data (mostly 2D sideband) rest MC.

ATLAS WVγ results

arXiv:1707.05597 submitted to EPJC

- Fiducial cross section measured in fully leptonic channel (Expected significance 1.6σ observed 1.4σ).
  - Measurement:

$$\sigma_{\text{fid}}^{e\nu\mu\nu\gamma} = 1.5 \pm 0.9(\text{stat.}) \pm 0.5(\text{syst.})\,\text{fb}$$

- Set 95% C.L. limits on the production cross-section in both channels too.

		Observed limit [fb]	Expected limit [fb]	σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	3.7	$2.1^{+0.9}_{-0.6}$	2.0
Semileptonic	$e\nu jj\gamma$	10	16^{+6}_{-4}	2.4
	$\mu\nu jj\gamma$	8	10^{+4}_{-3}	2.2
	$\ell\nu jj\gamma$	6	$8.4^{+3.4}_{-2.4}$	2.3

- Results are in agreement with SM expectations.

Search for WWW(→lνlνlν)

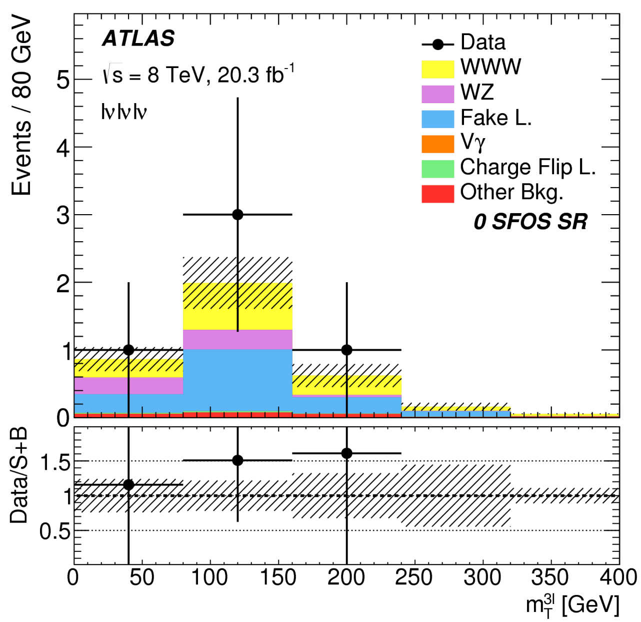
ATLAS performed search of WWW(→lνlνlν) channel.

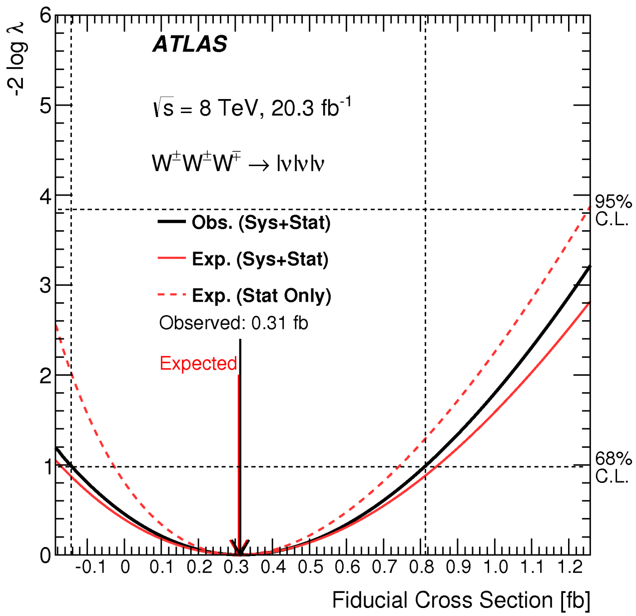
- Fiducial definition:

$\ell\nu\ell\nu\ell\nu$	0 SFOS	1 SFOS	2 SFOS
Preselection	Exactly three charged leptons with $p_T > 20$ GeV		
E_T^{miss}	-	$E_T^{miss} > 45$ GeV	$E_T^{miss} > 55$ GeV
Same-flavour dilepton mass	$m_{\ell\ell} > 20$ GeV	-	
Angle between trilepton and $\vec{p}_T^{miss}$	$\lvert\phi^{3\ell} - \phi^{\vec{p}_T^{miss}}\rvert > 2.5$		
Z boson veto	$\lvert m_{ee} - m_Z\rvert > 15$ GeV	$m_Z - m_{SFOS} > 35$ GeV or $m_{SFOS} - m_Z > 20$ GeV	$\lvert m_{SFOS} - m_Z\rvert > 20$ GeV
Jet veto	At most one jet with $p_T > 25$ GeV and $\lvert\eta\rvert < 4.5$		
b-jet veto	No identified b−jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$		

- Backgrounds (0-SFOS):
  WZ (norm data), fakes (data), Charge flip (data), other MC.

SFOS=Same flavor opposite sign pairs





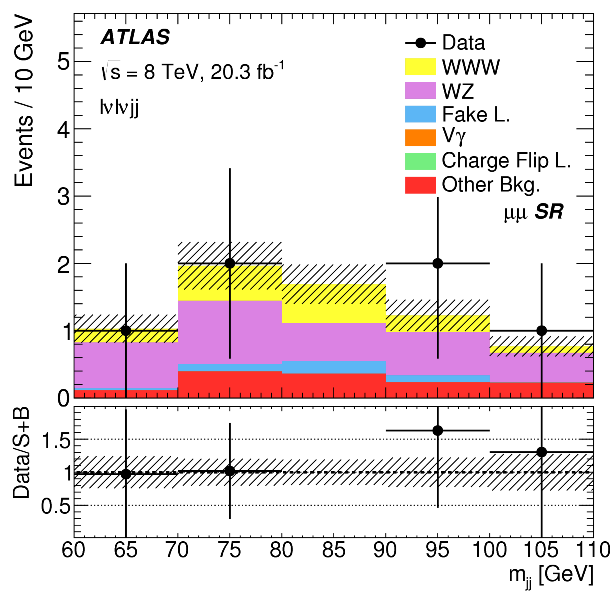
Search for WWW(→lνlνjj)

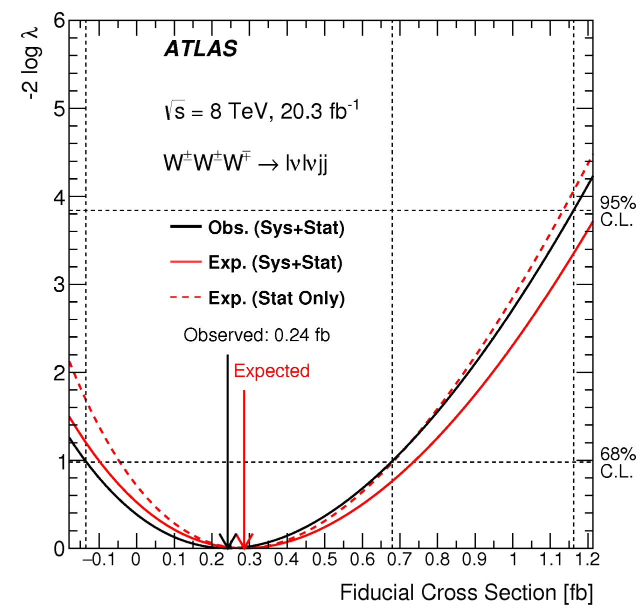
ATLAS performed search of WWW(→lνlνjj) channel.

- Fiducial definition:

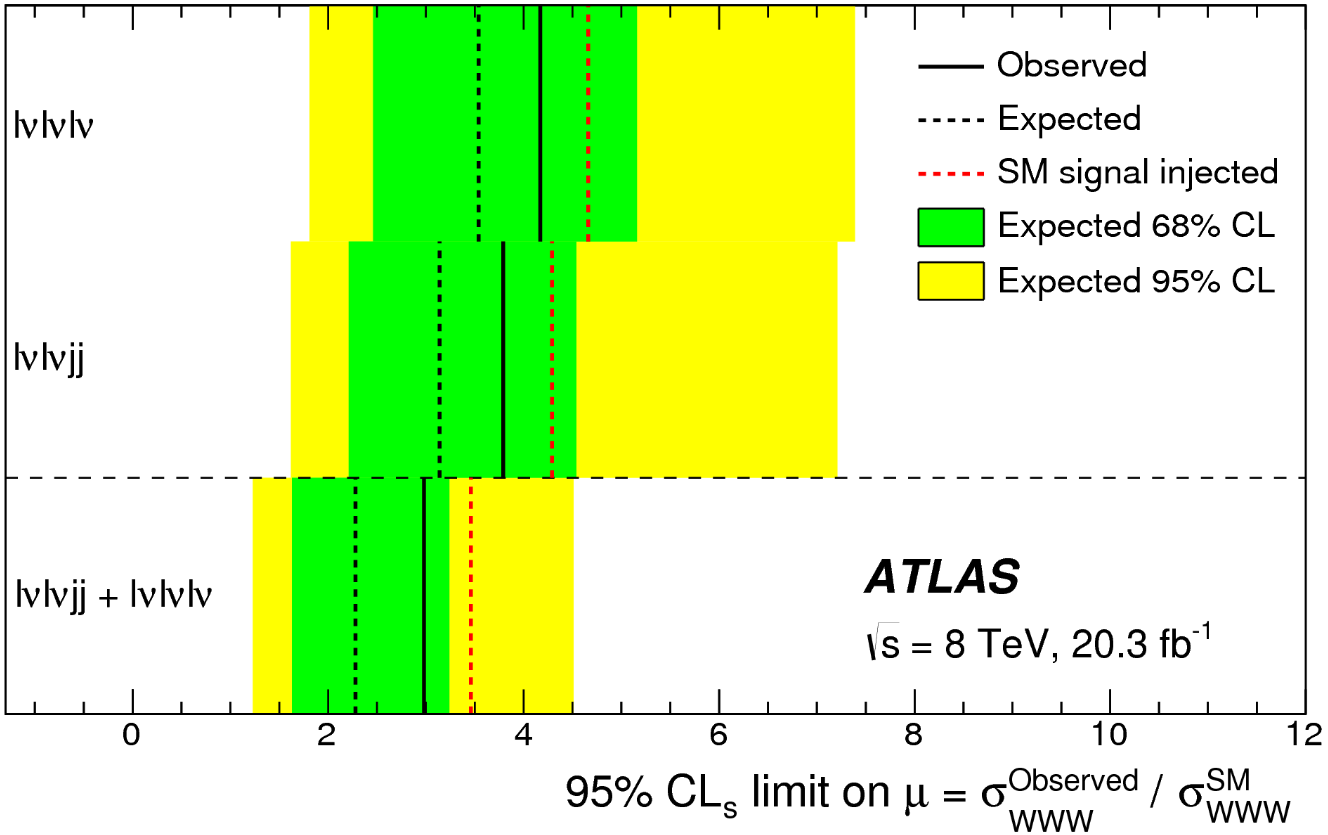
$\ell\nu\ell\nu jj$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Lepton	Exactly two same-charge leptons with $p_{\mathrm{T}} > 30$ GeV		
Jets	At least two jets with $p_{\mathrm{T}}(1) > 30$ GeV, $p_{\mathrm{T}}(2) > 20$ GeV and $\lvert\eta\rvert < 2.5$		
$m_{\ell\ell}$	$m_{\ell\ell} > 40$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV		-
m_{jj}	$65\ GeV < m_{jj} < 105$ GeV		
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$		
Z boson veto	$m_{ee} < 80$ GeV or $m_{ee} > 100$ GeV	-	
Third-lepton veto	No third lepton with $p_{\mathrm{T}} > 6$ GeV and $\lvert\eta\rvert < 2.5$ passing looser identification requirements		
b-jet veto	No identified $b-$jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$		

- Backgrounds semi leptonic (μ±μ±):
  WZ (check CR), fakes (data), Charge flip (data), other MC.





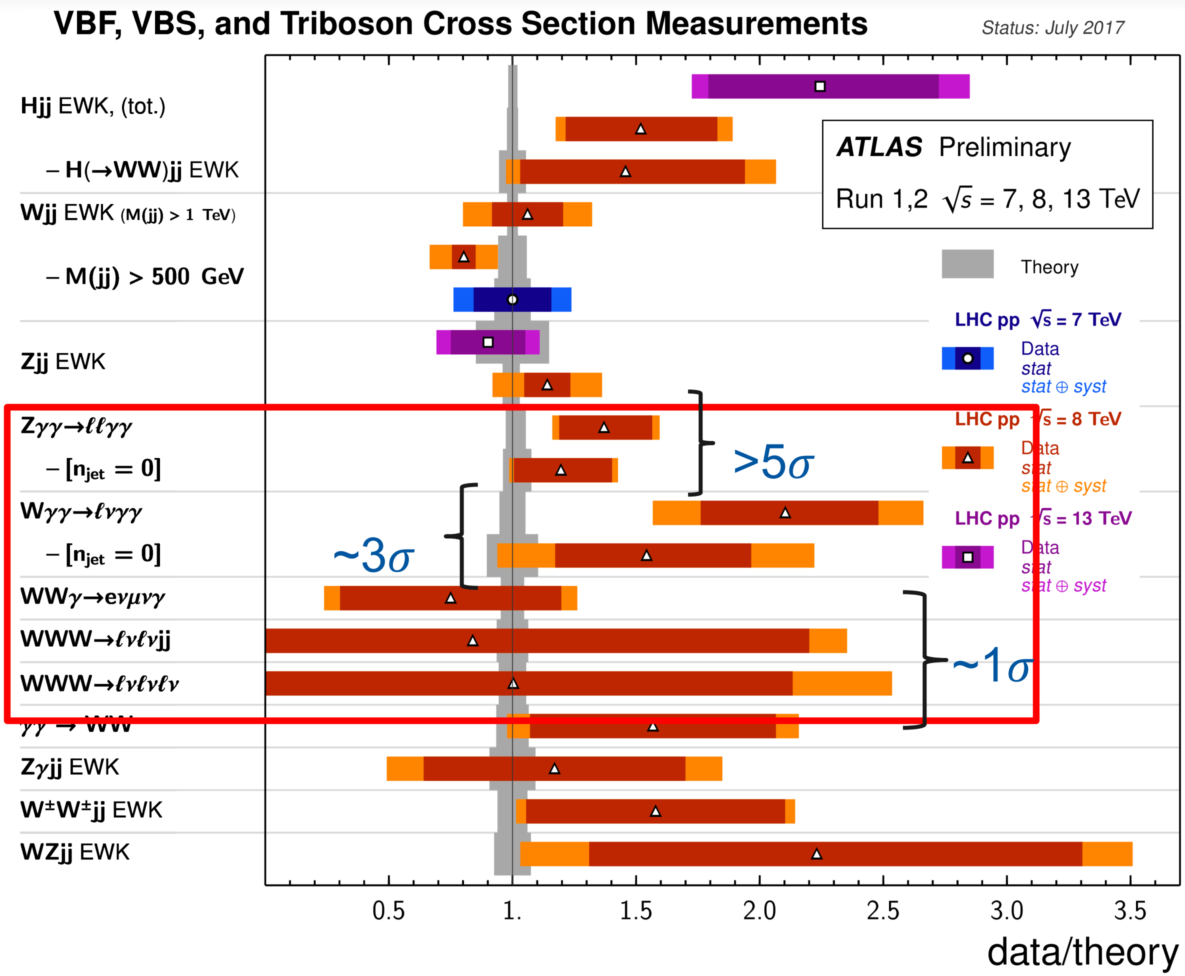
ATLAS WWW results

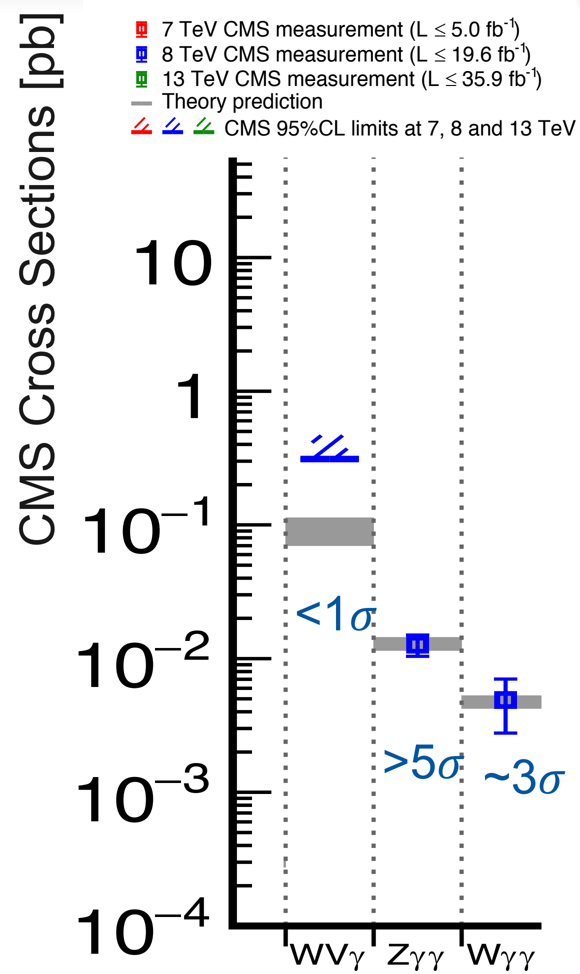


- Combination of 2 channels gives sensitivity of 1σ (expected and observed).
  - Good agreement with theory.
- Set 95% C.L. limits on the total production cross section (σ_{tot}^{obs}<730 fb, σ_{tot}^{exp}~230 fb).

Overview of SM measurements

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined





→Only 8 TeV results available so far.

→Mostly statistically dominated. Largest systematic in all cases is on fake bkg model.

→Wait for 13 TeV results to come !

Outline

- Introduction
- SM analysis
- aQGC search
- Conclusions

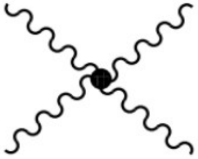
Search for BSM physics

- The SM is assumed to be a low effective theory of a more fundamental one at a scale beyond the current kinematic reach.

- Search for BSM physics using a model independent approach complementary to direct searches.
  - New physics in EW sector modify the triple and quartic self-interactions.
  - Dimension 8 operators only impact QGC with no effect on TGC.
  - The effective field theory can be parametrized using an effective Lagrangian:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j}$$

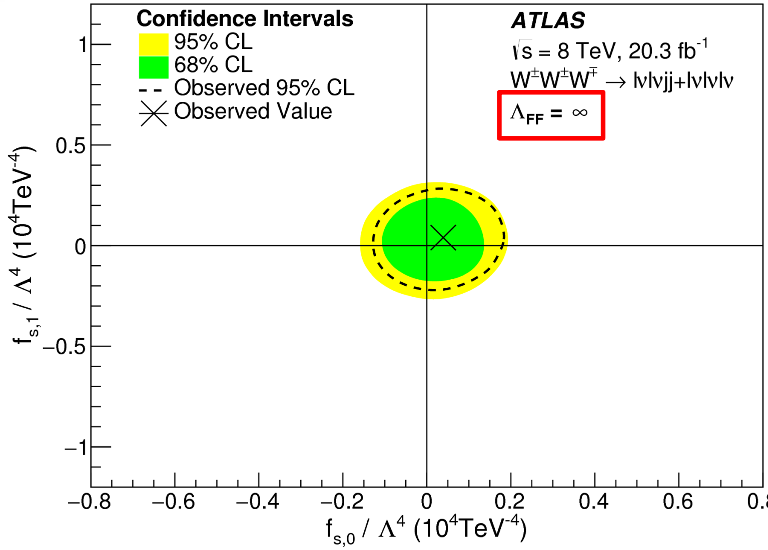
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X



18 independent aQGC (dim 8) operators

Unitarization

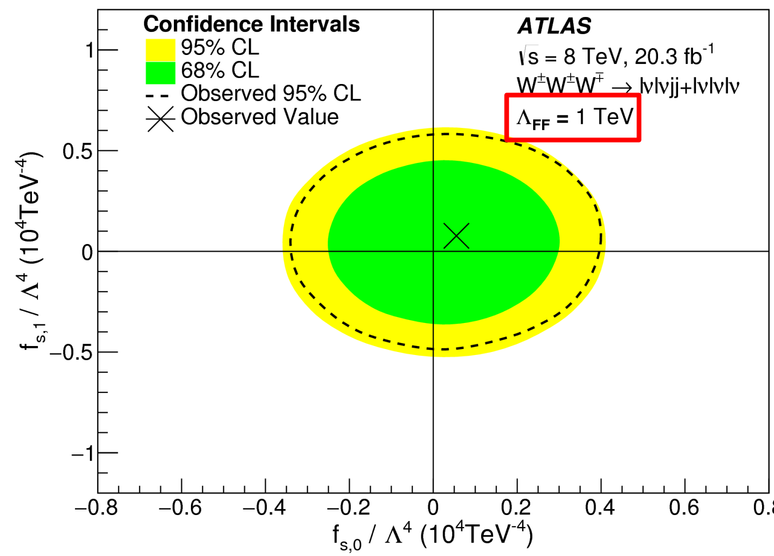
- With aQGCs, the unitarity is violated even in the presence of a SM Higgs at some scale.
  - Need to introduce a unitarization scheme.
  - Introducing a unitarization scheme introduce model dependence!



- In the search for aQGC in triboson final states, use the form factor unitarization:

$$\frac{1}{(1+\hat{s}/\Lambda_{FF}^2)^2}$$

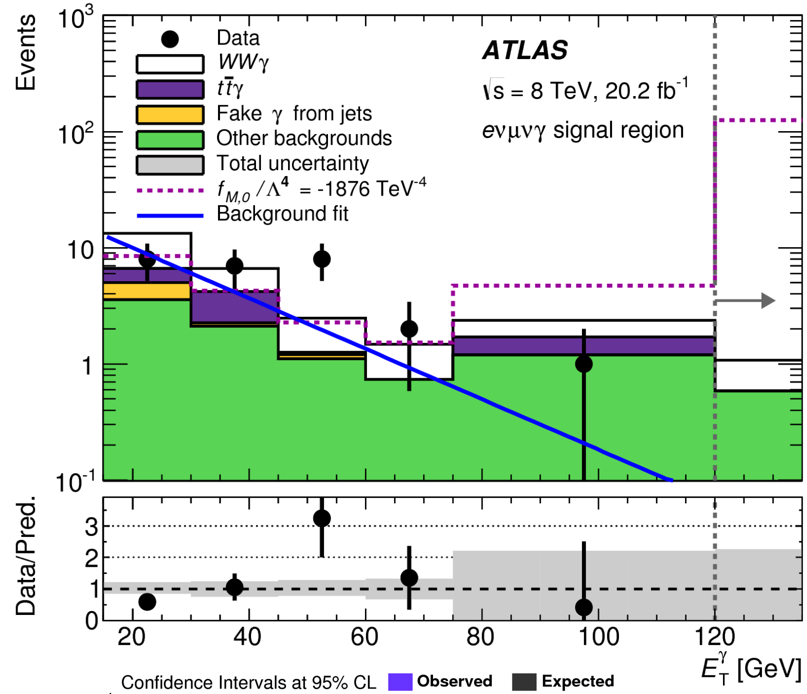
  - Weakly motivated, but easy to implement.

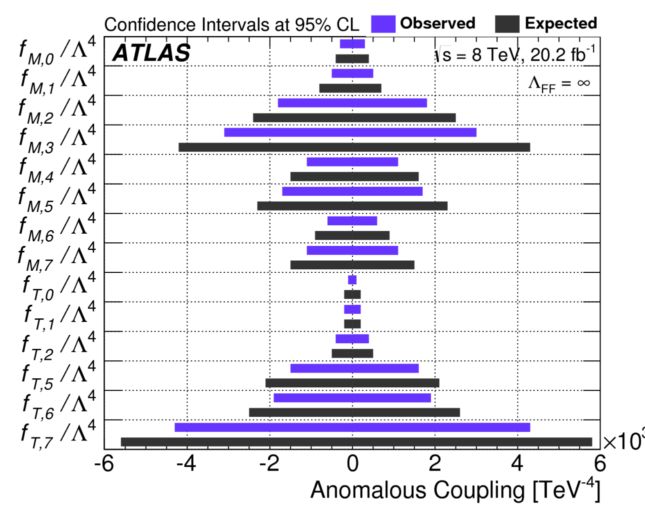


aQGC search principle

arXiv:1707.05597 submitted to EPJC

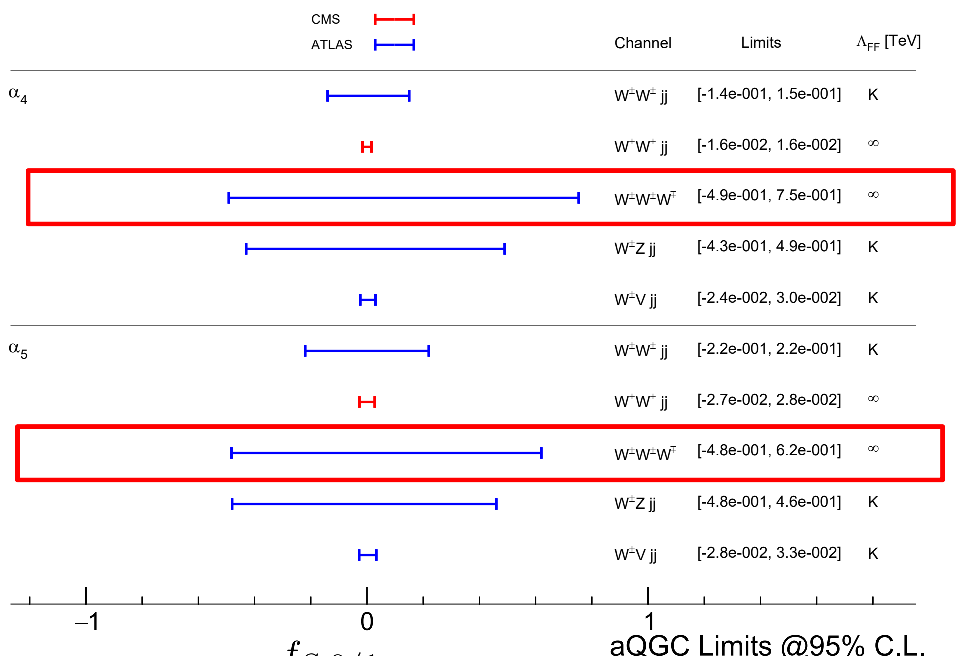
- Start from SM measurement:
  - Use SM signal+background model to describe some kinematic variable sensitive to new physics (E_T^{γ}, p_T^{VV}, m^{VV}, m_T^{VV}, ...) .
  - Generate, simulate and plug new physics signal (usually use VBFNLO or Madgraph).
  - Potentially re-optimize analysis cuts to increase discovery potential.
  - Set 95% C.L. limits using profile likelihood ratio.

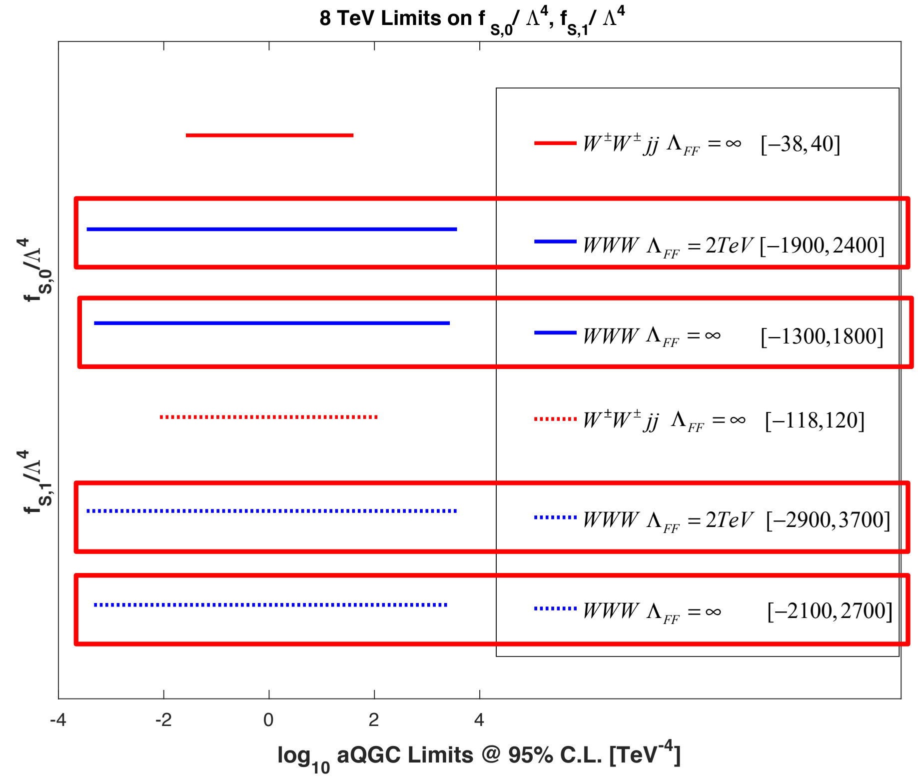




Arxiv: 1610.07572 **Submitted to: Rev.Mod.Phys.**

Limits on dim4: α4, α5 dim 8: F_{S0}, F_{S1}



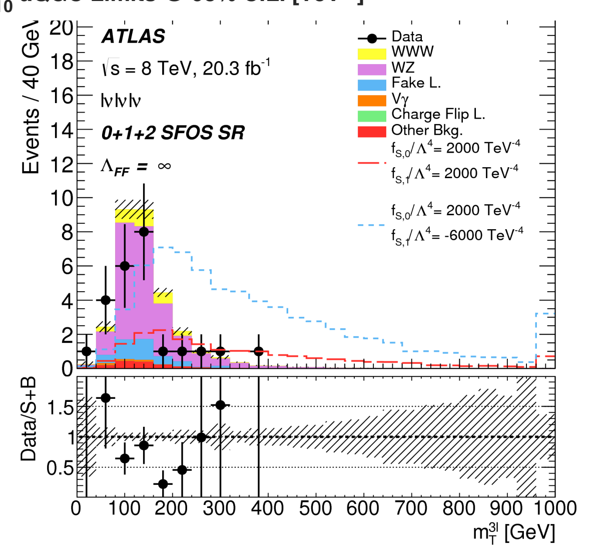


$$\alpha_{4/5} \longleftrightarrow \frac{f_{S,0/1}}{\Lambda^4}$$

Conversion factor:

$$\rightarrow WWWW \text{vertex}: \alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8} \qquad \alpha_4 + 2\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

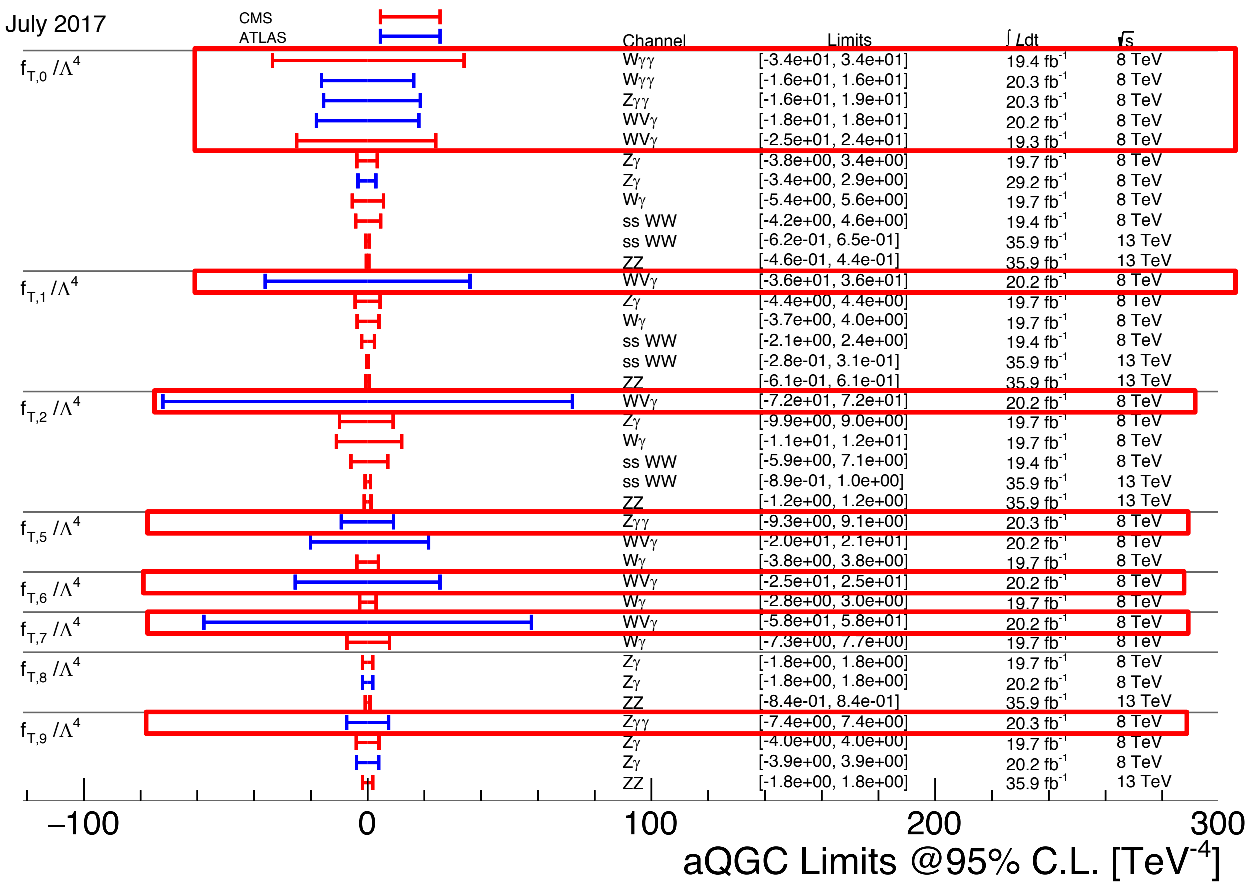
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

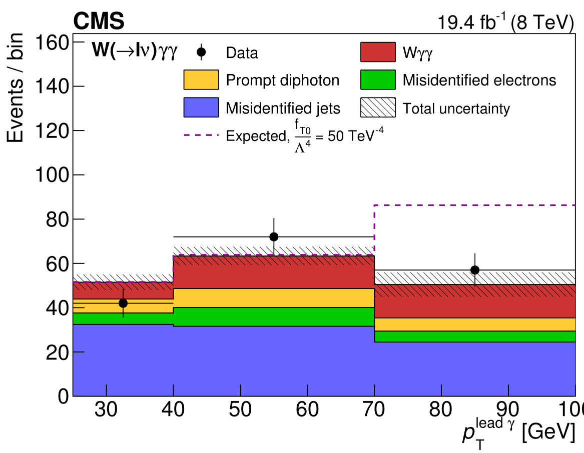


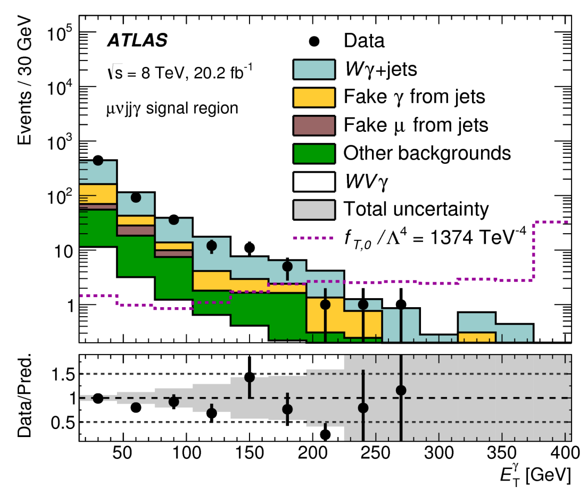
→Worse than VBS but nice cross check.

Limits on dim 8: F_T

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC





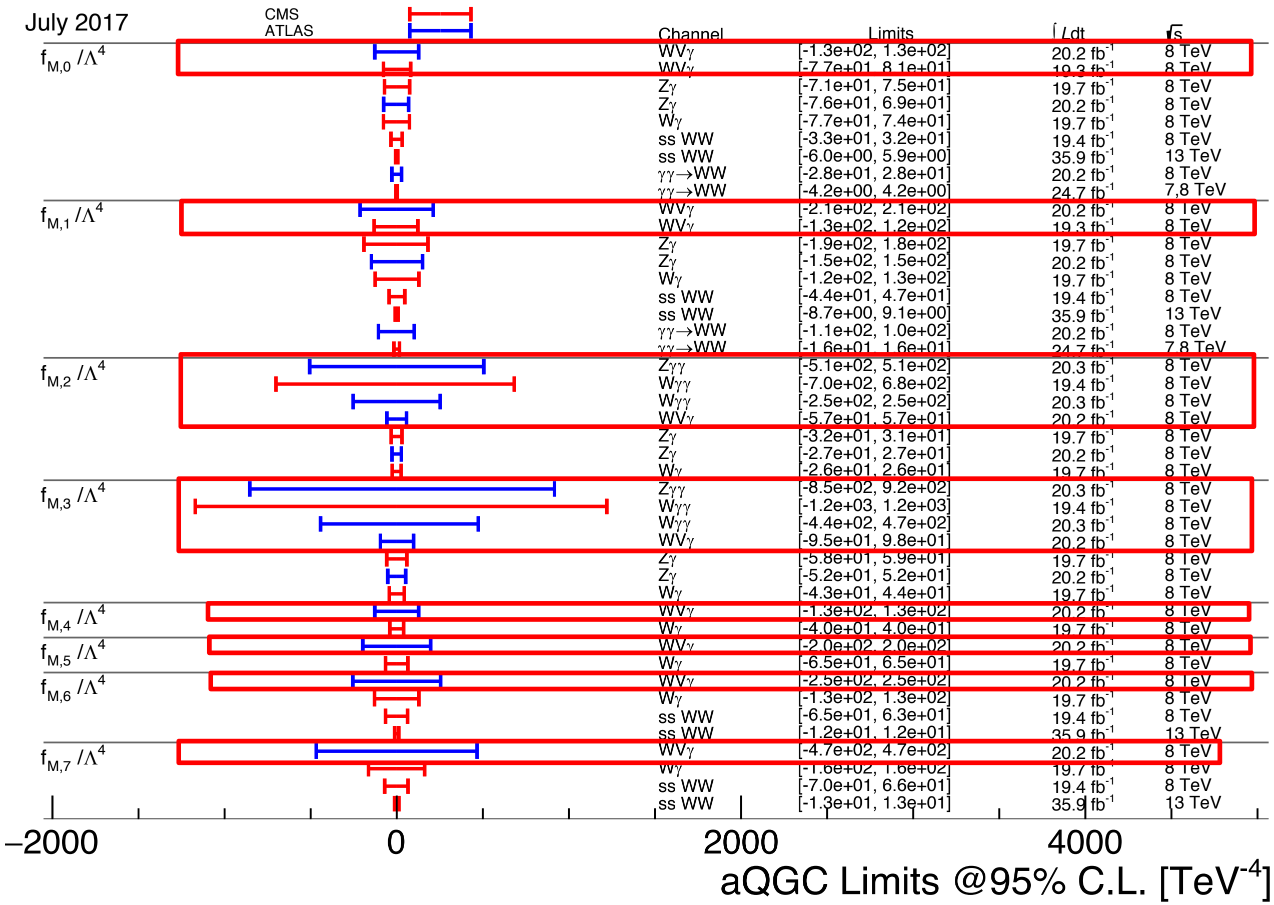


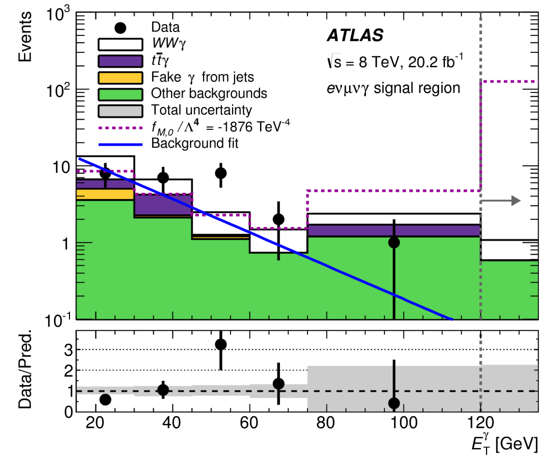
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

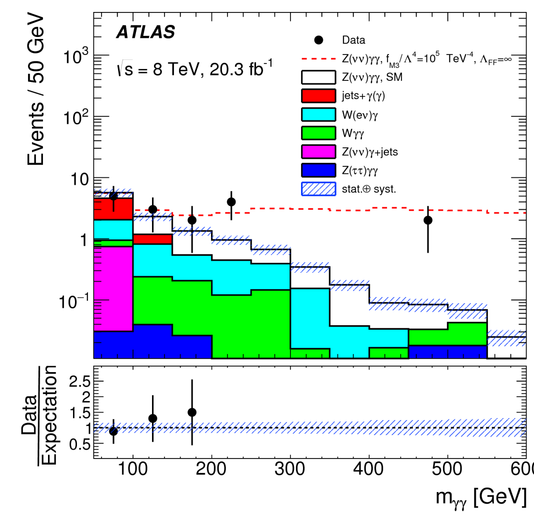
→Worse than VBS but nice cross check.

Limits on dim 8: F_M

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC







	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

→Worse than VBS
but nice cross check.

Outline

- Introduction
- SM analysis
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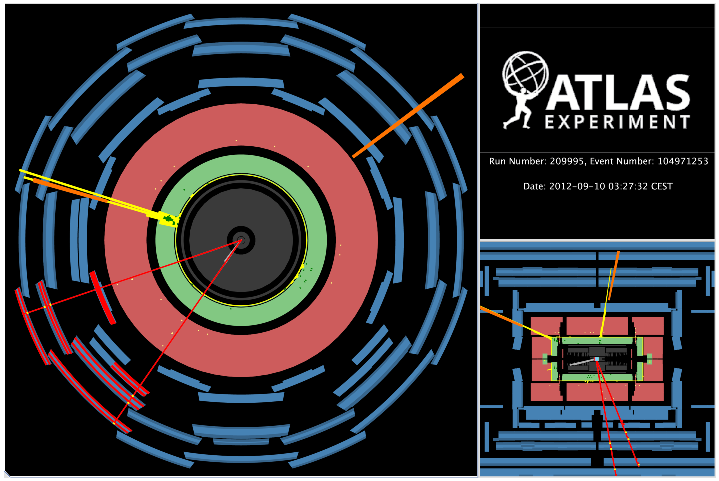
Conclusions

- First observation of triboson process at hadron collider was done during LHC run1 in the $Z\gamma\gamma$ final state!



- So far good agreement between measurements and SM predictions.
- Tribosons are sensitive to quartic gauge coupling, and all the analyses that have been done so far are used to set limits on new physics through aQGCs.
- By the end of run2 should have the first evidence for more massive triboson final state (WWW, WWγ, WZγ).

Back-up

W(→lν)γγ @ 8 TeV ATLAS

ATLAS: Phys. Rev. Lett. 115, 031802 (2015)

	Electron channel	Muon channel	Electron channel	Muon channel
	$N_{\text{jet}} \geq 0$		$N_{\text{jet}} = 0$	
$W\gamma$j + Wjj	15.3 ± 4.8(stat.) ± 5.3(syst.)	30.5 ± 7.7(stat.) ± 6.8(syst.)	5.8 ± 2.1(stat.) ± 2.0(syst.)	14.4 ± 4.9(stat.) ± 4.9(syst.)
$\gamma\gamma$ + jets	1.5 ± 0.6(stat.) ± 1.0(syst.)	11.0 ± 4.0(stat.) ± 4.9(syst.)	0.2 ± 0.2(stat.) ± 0.2(syst.)	6.1 ± 3.5(stat.) ± 3.1(syst.)
$Z\gamma$	11.2 ± 1.1(stat.)	3.9 ± 0.2(stat.)	2.4 ± 0.5(stat.)	2.8 ± 0.2(stat.)
Other backgrounds	2.2 ± 0.6(stat.)	6.7 ± 2.0(stat.)	0.3 ± 0.1(stat.)	1.1 ± 0.3(stat.)
Total background	30.2 ± 5.0(stat.) ± 5.4(syst.)	52.1 ± 8.9(stat.) ± 8.4(syst.)	8.7 ± 2.2(stat.) ± 2.0(syst.)	24.4 ± 6.0(stat.) ± 5.8(syst.)
Data	47	110	15	53

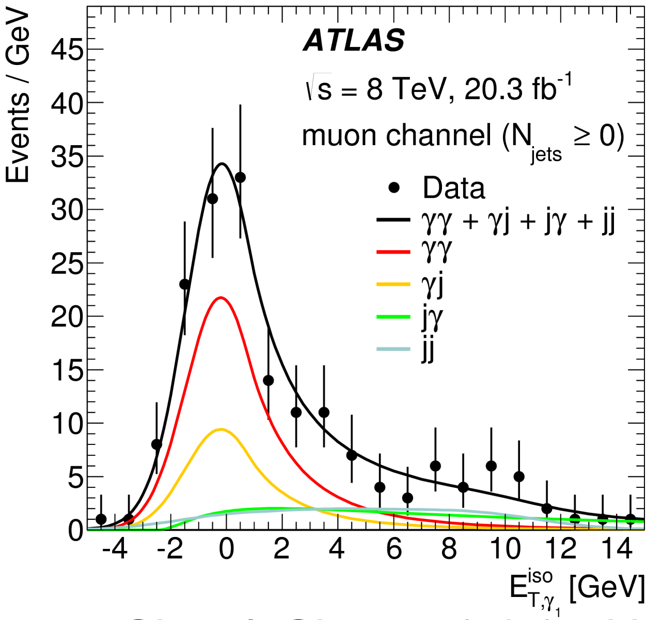
	Inclusive Selection	Exclusive Selection
Correction Factor ϵ	(40.4 ± 0.7 (stat.)) %	(39.7 ± 1.0 (stat.)) %
Acceptance A	(89.2 ± 0.3 (stat.)) %	(89.7 ± 0.4 (stat.)) %
Efficiency C	(45.2 ± 0.8 (stat.)) %	(44.3 ± 1.1 (stat.)) %
Relative systematic error on the efficiency C [%]		
Systematic Source	syst. unc.	syst. unc.
Muon Eff Scale Factor	0.0	0.0
Muon Energy Scale	0.3	0.3
Muon Isolation Eff.	0.2	0.1
Muon Resolution ID	0.1	0.1
Muon Resolution MS	2.1	1.4
Photon Energy Scale	1.0	1.1
Photon Energy Resol.	0.3	0.5
Photon ID Efficiency	0.8	0.9
MET Reso Soft Terms	0.4	0.8
MET Scale Soft Terms	1.0	1.1
Jet Energy Scale	3.2	6.0
Jet Energy Resolution	0.8	1.4
Jet Vertex Fraction	–	0.3
Pileup reweight	0.0	0.5
Trigger	0.5	0.5
Total rel. syst. error on C [%]	4.3	6.7

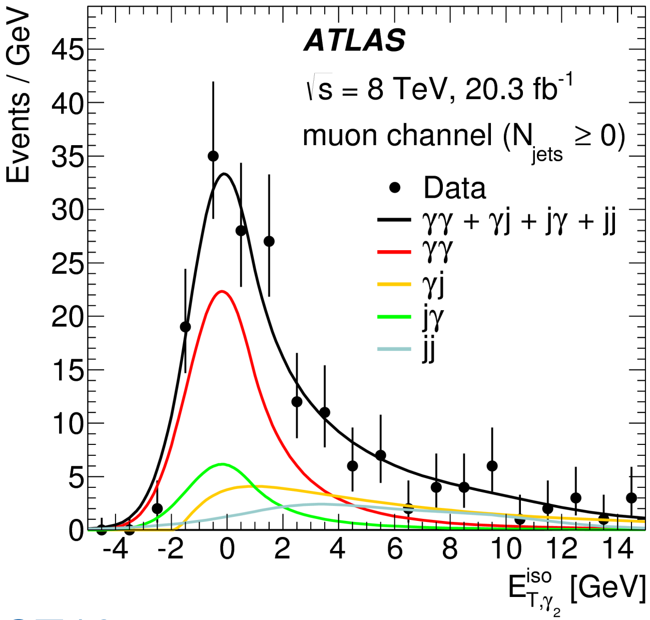
	Inclusive Selection	Exclusive Selection
Correction Factor ϵ	(19.6 ± 0.5 (stat.)) %	(15.1 ± 0.7 (stat.)) %
Acceptance A	(82.5 ± 0.4 (stat.)) %	(82.5 ± 0.6 (stat.)) %
Efficiency C	(23.7 ± 0.6 (stat.)) %	(18.4 ± 0.8 (stat.)) %
Relative systematic error on the efficiency C [%]		
Systematic Source	syst. unc.	syst. unc.
Electron Reconstruction Eff.	0.1	0.1
Electron ID Uncert	0.2	0.2
Electron Isolation Eff.	0.0	0.0
EM Energy Scale	2.4	4.5
EM Energy Resolution	0.3	0.3
Photon ID Eff	0.8	0.9
MET Reso Soft Terms	0.6	1.2
MET Scale Soft Terms	0.3	1.3
Jet Energy Resol	1.5	1.4
Jet Energy Scale	5.3	6.2
Jet Vertex Fraction	–	0.4
Pileup Reweighting	0.2	0.2
Trigger	0.7	0.7
Total rel. syst. error on C [%]	6.2	8.2

W(→lν)γγ @ 8 TeV ATLAS

ATLAS: Phys. Rev. Lett. 115, 031802 (2015)

W+jets and Wγ+jet (2D-template fit of isolation and Photon ID), γγ+jet estimated from data (ATLAS), Zγ scaled in CR.





Signal: Sherpa 1.4.1 with CT10

Sherpa 1.4.1 with CT10: *Zγ,Zγγ,WZ W(τν)γγ*

MC@NLO 4.02 with Herwig 6.520 and Jimmy 4.30 +CT10: tt, single top, WW

Powheg+Pythia 8.163 with CT10: ZZ

W/Zγγ @ 8 TeV CMS

CMS: arXiv:1704.00366 submitted to JHEP

W+jets and Wγ+jet (2D-template fit of isolation and Photon ID), γγ+jet estimated from data, Zγ scaled in CR.

$W\gamma\gamma$	Electron channel	Muon channel
Jet $\rightarrow\gamma$ misidentification	22 ± 6	63 ± 12
Electron $\rightarrow\gamma$ misidentification	20 ± 2	—
Prompt diphoton	7 ± 1	14 ± 2
Total background	49 ± 6	77 ± 12
Expected signal	13 ± 1	25 ± 3
Data	63	108

$Z\gamma\gamma$	Electron channel	Muon channel
Jet $\rightarrow\gamma$ misidentification	62 ± 8	68 ± 9
Prompt diphoton	0.3 ± 0.1	0.6 ± 0.2
Total background	62 ± 8	69 ± 9
Expected signal	56 ± 8	73 ± 10
Data	117	141

Z+jets and Zγ+jet (2D-template fit of isolation and Photon ID), other backgrounds negligible.

W/Zγγ @ 8 TeV CMS

CMS: arXiv:1704.00366 submitted to JHEP

	Wγγ		Zγγ	
	e channel	μ channel	ee channel	μμ channel
Signal simulation				
Simulation statistical uncertainty	2.8	2.4	3.3	2.9
Trigger	0.5	0.3	1.3	1.2
Lepton and photon ID and energy scale	4.1	3.0	5.3	4.3
p_T^{miss} scale	1.5	1.4	—	—
Pileup	0.5	0.2	1.3	0.4
PDFs, renorm. and fact. scales	1.5	1.6	1.2	1.3
Background				
Misidentified jet	36.6	37.2	15.1	12.5
Misidentified electron	6.9	—	—	—
Prompt diphoton	6.7	5.8	0.2	0.3
Summary				
Total statistical	47.8	29.6	16.6	13.7
Total systematic	38.3	37.9	16.5	13.7
Integrated luminosity	2.6	2.6	2.6	2.6

Signal @NLO using Madgraph5_aMC@NLO (V5.2.2) with NNPDFNLO3.0, and pythia 8.1

Backgrounds with diboson and triboson from Madgraph5_aMC@NLO (V5.2.2) at LO with CTQ6L1 with Pythia 6.4.

Diboson norm to MCFM(6.6)@NLO and tribosonMadgraph5_aMC@NLO (V5.2.2).

Zγγ @ 8 TeV ATLAS

ATLAS: *Phys. Rev. D 93, 112002 (2016)*

	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
	$N_{\text{jets}} \geq 0$		$N_{\text{jets}} = 0$	
$N^{\text{obs}}_{Z\gamma\gamma}$	43	37	29	22
$N^{j\to\gamma}_{Z\gamma\gamma}$	$5.8 \pm 1.0 \pm 1.4$	$10.9 \pm 1.1 \pm 2.8$	$3.08 \pm 0.73 \pm 0.75$	$6.4 \pm 0.9 \pm 1.8$
$N^{\text{Other BKG}}_{Z\gamma\gamma}$	$0.42 \pm 0.08 \pm 0.18$	$0.194 \pm 0.047 \pm 0.097$	$0.24 \pm 0.05 \pm 0.11$	$0.105 \pm 0.028 \pm 0.055$
$N^{\text{sig}}_{Z\gamma\gamma}$ (SHERPA)	$25.7 \pm 0.5 \pm 1.6$	$29.5 \pm 0.6 \pm 1.7$	$18.9 \pm 0.5 \pm 1.5$	$21.8 \pm 0.5 \pm 1.7$

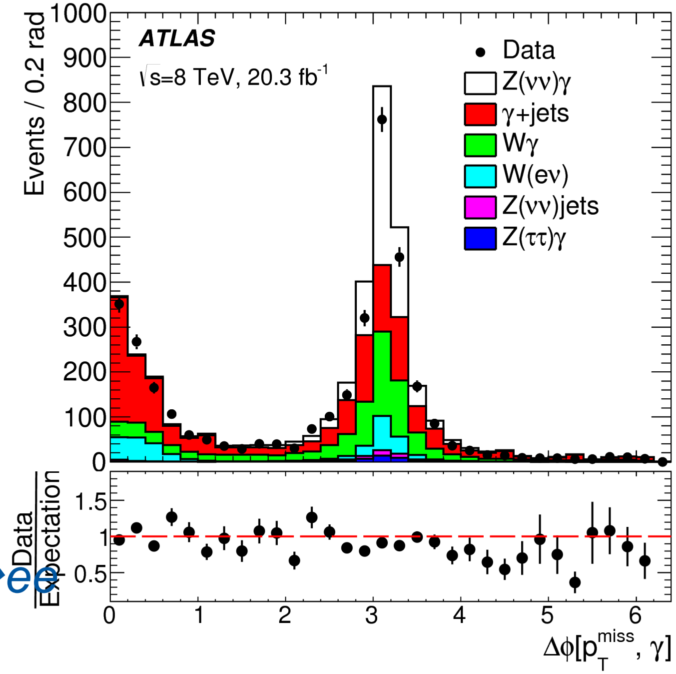
Z+jets and Zγ+jet (2D-template fit of isolation and Photon ID), other backgrounds negligible.

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	$\nu\bar{\nu}\gamma$	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$	$\nu\bar{\nu}\gamma\gamma$
MC statistical uncertainty	0.3 (0.3)	0.2 (0.3)	0.1 (0.1)	1.9 (2.3)	1.8 (2.1)	0.6 (0.8)
Efficiencies :						
Trigger	0.2 (0.2)	0.5 (0.5)	1.9 (1.9)	0.1 (0.1)	0.5 (0.5)	0.2 (0.2)
Photon identification	1.5 (1.5)	1.5 (1.5)	0.5 (0.5)	2.1 (2.1)	2.1 (2.1)	1.9 (1.9)
Photon isolation	0.5 (0.5)	0.5 (0.5)	4.5 (4.3)	1.2 (1.2)	1.2 (1.2)	2.8 (2.8)
Lepton reconstruction and identification	1.6 (1.6)	0.9 (0.9)	– (–)	1.6 (1.6)	0.9 (0.9)	– (–)
Lepton isolation and impact parameter	2.2 (2.2)	2.2 (2.2)	– (–)	2.2 (2.2)	2.2 (2.2)	– (–)
Jet vertex fraction	– (0.5)	– (0.6)	– (0.1)	– (0.5)	– (0.6)	– (0.2)
Energy/momentum scale and resolution :						
Electromagnetic energy scale	2.3 (2.5)	1.2 (1.3)	2.1 (2.4)	2.5 (2.7)	1.8 (1.9)	2.0 (2.8)
Electromagnetic energy resolution	<0.05 (<0.05)	<0.05 (<0.05)	<0.05 (0.1)	0.2 (0.3)	0.3 (0.3)	0.4 (0.5)
Muon momentum scale	– (–)	0.1 (0.2)	– (–)	– (–)	0.3 (0.2)	– (–)
Muon momentum resolution	– (–)	<0.05 (<0.05)	– (–)	– (–)	0.5 (0.5)	– (–)
Jet energy scale	– (1.9)	– (1.9)	<0.05 (2.2)	– (2.2)	– (1.8)	0.7 (2.9)
Jet energy resolution	– (1.2)	– (1.4)	<0.05 (1.0)	– (1.2)	– (0.8)	0.1 (1.9)
$E_{\text{T}}^{\text{miss}}$ soft-term energy scale	– (–)	– (–)	0.3 (0.5)	– (–)	– (–)	1.3 (1.7)
$E_{\text{T}}^{\text{miss}}$ soft-term energy resolution	– (–)	– (–)	<0.05 (<0.05)	– (–)	– (–)	0.4 (0.7)
Pileup simulation	0.8 (0.8)	0.6 (0.7)	0.2 (0.4)	0.8 (1.0)	1.1 (1.1)	0.6 (0.9)
Total, without MC statistical uncertainty	4.0 (4.7)	3.2 (4.1)	5.3 (5.9)	4.5 (5.3)	4.1 (4.6)	4.3 (6.0)

Zγγ @ 8 TeV ATLAS

ATLAS: *Phys. Rev. D 93, 112002 (2016)*

	$N_{\text{jets}} \geq 0$	$N_{\text{jets}} = 0$
$N^{\text{obs}}_{Z\gamma\gamma}$	46	19
$N^{\text{jets}+\gamma(\gamma)}_{Z\gamma\gamma}$	$12.2 \pm 6.7 \pm 1.8$	$2.9 \pm 4.0 \pm 0.4$
$N^{W(\ell\nu)\gamma\gamma}_{Z\gamma\gamma}$	$3.6 \pm 0.1 \pm 3.6$	$1.0 \pm 0.1 \pm 1.0$
$N^{W(e\nu)\gamma}_{Z\gamma\gamma}$	$10.4 \pm 0.5 \pm 2.1$	$3.47 \pm 0.28 \pm 0.69$
$N^{Z(\nu\bar{\nu})\gamma+\text{jets}}_{Z\gamma\gamma}$	$0.71 \pm 0.71 \pm 0.90$	$0.71 \pm 0.71 \pm 0.75$
$N^{Z(\tau^+\tau^-)\gamma\gamma}_{Z\gamma\gamma}$	$0.381 \pm 0.055 \pm 0.027$	$0.141 \pm 0.036 \pm 0.010$
$N^{\text{bkg}}_{Z\gamma\gamma}$	$27.2 \pm 6.8 \pm 4.6$	$8.3 \pm 4.1 \pm 1.5$
$N^{\text{sig}}_{Z\gamma\gamma}$ (SHERPA)	$7.54 \pm 0.07 \pm 0.34$	$4.80 \pm 0.06 \pm 0.29$



Backgrounds:

- Mismeasured jets determined using ABCD
- e→γ misID determined using fake rates from *Z→ee*
- *Wγγ* scaled from data.

Signal: Sherpa 1.4.1 with CT10

Sherpa 1.4.1 with CT10: *Zγ,Wγγ*

Madgraph_aMC@NLO 5.02 with Herwig 6.520 and Jimmy 4.30 +CT10: tt, ttγ single top, WW

Powheg+Pythia 8.163 with CT10: ZZ,WZ

γ+jets: Sherpa 1.4, cross check with Pythia 8.10

CMS W(→lν)V(→jj)γ

Process	Muon channel number of events	Electron channel number of events
SM WWγ	6.6 ± 1.5	5.0 ± 1.1
SM WZγ	0.6 ± 0.1	0.5 ± 0.1
Wγ + jets	136.9 ± 10.5	101.6 ± 8.5
WV + jet, jet $\rightarrow \gamma$	33.1 ± 4.8	21.3 ± 3.3
MC $t\bar{t}\gamma$	12.5 ± 3.0	9.1 ± 2.2
MC single top quark	2.8 ± 0.8	1.7 ± 0.6
MC Zγ + jets	1.7 ± 0.1	1.5 ± 0.1
Multijets	—	7.2 ± 5.1
Total prediction	194.2 ± 11.5	147.9 ± 10.7
Data	183	139

Process		Cross section [pb]
SM WWγ	(NLO)	0.090 ± 0.021
SM WZγ	(NLO)	0.012 ± 0.003
Wγ + jets	(Data)	10.9 ± 0.8
Zγ + jets	(LO)	0.63 ± 0.13
$t\bar{t}\gamma$	(LO)	0.62 ± 0.12
Single t + γ(inclusive)	(NLO)	0.31 ± 0.01

- Backgrounds:
  - Wγ+*jets:* sideband fit in m_{jj}.
  - Jets→γ extrapolated from data
  - Jets→*l* fit To E_T^{Miss}.
  - Other bkg estimated for MC.

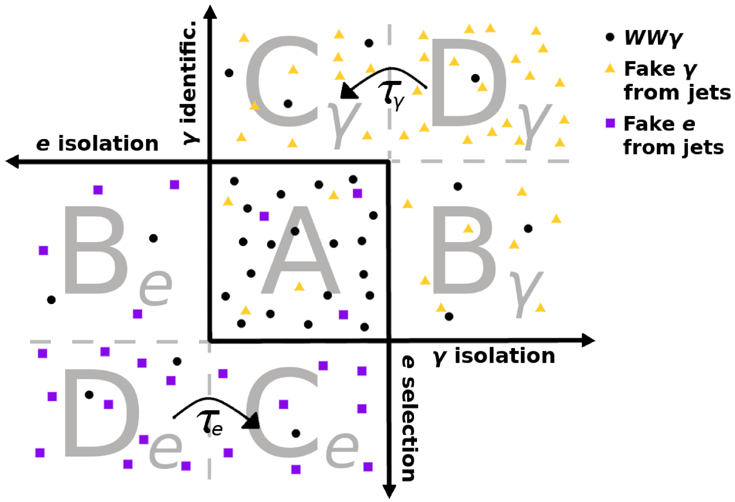
Signal+bkg:
Madgraph 5.1.3.22+CTEQ6L1

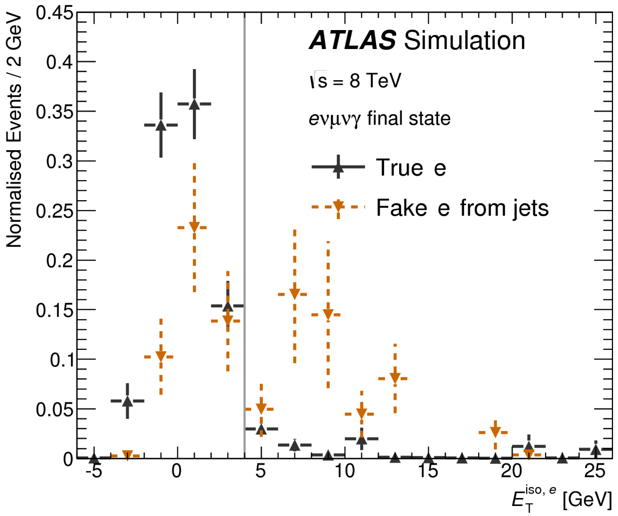
Single top: Powheg+CTEQ6M1

NLO/LO k-factor derived from Madgraph

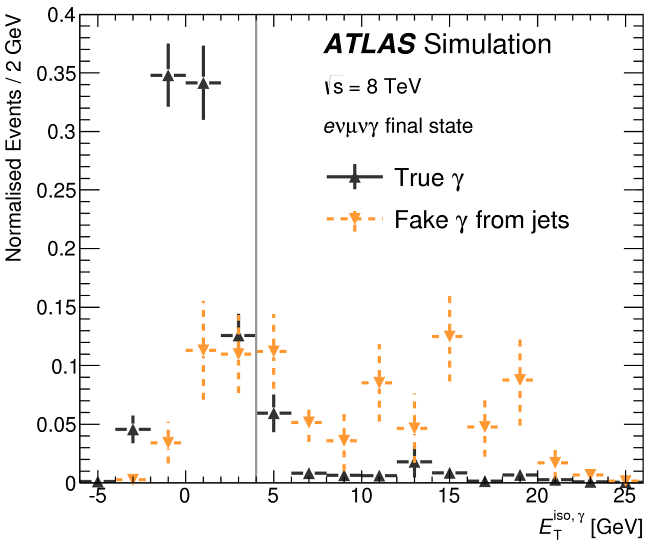
ATLAS WVγ

arXiv:1707.05597 submitted to EPJC





Process	Events	Estimation Method
$t\bar{t}\gamma$	4.1 ± 1.9	MC simulation
$Z\gamma$	2.7 ± 1.2	MC simulation
$WZ\gamma$	2.7 ± 0.6	MC simulation
Fake γ from e	2.3 ± 0.6	Corrected simulation
Fake γ from jets	$1.7\,^{+3.3}_{-1.4}$	2D sideband method
$WW\gamma$ (τ contribution)	1.0 ± 0.1	MC simulation
Wt	0.3 ± 0.1	MC simulation
ZZ	0.2 ± 0.1	MC simulation
Fake μ from jets	0.1 ± 0.1	MC simulation
Fake e from jets	$0.0\,^{+0.6}_{-0.0}$	2D sideband method
Total background	15.1 ± 4.1	Sum of components
Expected signal	12.2 ± 1.1	Corrected VBFNLO
Data	26	Measurement



ATLAS WVγ

arXiv:1707.05597 submitted to EPJC

Process	Electron Channel	Muon Channel	Estimation Method
$W\gamma$ + jets	324 ± 11	407 ± 11	Simultaneous fit
Fake γ from jets	82 ± 7	117 ± 9	Simultaneous fit
Fake ℓ from jets	57 ± 6	27 ± 5	Simultaneous fit
$t\bar{t}\gamma$	35 ± 6	46 ± 7	MC simulation
Fake γ from e	33 ± 12	3 ± 1	Corrected simulation
$Z\gamma$ + jets	19 ± 4	20 ± 3	MC simulation
$WV\gamma$ (τ contribution)	< 1	< 1	MC simulation
Total background	552 ± 38	621 ± 31	Sum of components
Expected signal	14 ± 2	18 ± 2	Corrected VBFNLO
Data	490	599	Measurement

Signal with Sherpa 2.1.1 and CT10NLO @LO
normalised to NLO with VBFNLO.

Backgrounds from WZ, ZZ, and $Z\gamma$ diboson production were simulated with up to three additional partons in the final state using the SHERPA event generator (versions 1.4.1, 1.4.5, and 1.4.1 respectively) with the CT10NLO PDF set. Top quark pair production in association with a photon ($t\bar{t}\gamma$) was generated with the MadGraph 5.2.1.0 event generator using the CTEQ6L1 PDF set and interfaced to PYTHIA 8.183 [35] for the simulation of the hadronisation and the underlying event. The cross-section was normalised using the computations of Ref. [36] which were performed at NLO in α_S. The simultaneous production of top and antitop quarks ($t\bar{t}$) and the production of W bosons in association with top quarks (Wt) were generated at NLO in α_S with the POWHEG-BOX [37–39] program using the CT10f4 PDF set and being interfaced to PYTHIA 6.426 using the CTEQ6L1 PDF set. The background from Z bosons produced in association with jets (Z + jets) and from W-boson production in association with a photon ($W\gamma$ + jets)

		E_T^γ threshold [GeV]	Observed limit [fb]	Expected limit [fb]	SM Prediction σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	120	0.3	$0.3^{+0.3}_{-0.1}$	0.076
Semileptonic	$e\nu jj\gamma$	200	1.3	$1.3^{+0.5}_{-0.3}$	0.057
	$\mu\nu jj\gamma$	200	1.1	$1.1^{+0.5}_{-0.3}$	0.051
	$\ell\nu jj\gamma$	200	0.9	$0.9^{+0.3}_{-0.2}$	0.054

were generated with the ALPGEN [40] program interfaced to the HERWIG 6.520.2 [41] event generator for parton showering and hadronisation. The JIMMY [42] event generator was used to simulate the underlying event and the CTEQ6L1 PDF set was employed. All simulations that used the PYTHIA event generator employed the TAUOLA [43] program to compute the τ lepton decays. In samples that do not contain a prompt photon in the final state, the PHOTOS [44] program was employed to simulate photon radiation from final-state charged particles.

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ATLAS WWW

$\ell\nu\ell\nu\ell\nu$	0 SFOS	1 SFOS	2 SFOS
$W^{\pm}W^{\pm}W^{\mp}$ signal	1.34 ± 0.02 ± 0.07	1.39 ± 0.02 ± 0.08	0.61 ± 0.01 ± 0.03
WZ	0.59 ± 0.00 ± 0.07	11.9 ± 0.1 ± 1.3	9.1 ± 0.1 ± 1.0
Other prompt background	0.21 ± 0.01 ± 0.02	0.78 ± 0.02 ± 0.11	0.60 ± 0.02 ± 0.10
Charge-flip background	0.04 ± 0.00 ± 0.01	-	-
$V\gamma$	-	0.20 ± 0.13 ± 0.29	0.11 ± 0.10 ± 0.29
Fake-lepton background	1.5 ± 0.3 ± 1.4	1.9 ± 0.3 ± 1.9	0.49 ± 0.16 ± 0.47
Total background	2.4 ± 0.3 ± 1.4	14.8 ± 0.4 ± 2.3	10.3 ± 0.2 ± 1.2
Signal + background	3.7 ± 0.3 ± 1.4	16.2 ± 0.4 ± 2.3	10.9 ± 0.2 ± 1.2
Data	5	13	6

t3pt

$\ell\nu\ell\nu jj$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
$W^{\pm}W^{\pm}W^{\mp}$ signal	0.46 ± 0.03 ± 0.07	1.35 ± 0.05 ± 0.19	1.65 ± 0.06 ± 0.30
WZ	0.74 ± 0.13 ± 0.44	2.77 ± 0.27 ± 0.66	3.28 ± 0.29 ± 0.71
Other prompt background	0.46 ± 0.05 ± 0.16	1.33 ± 0.10 ± 0.38	1.33 ± 0.15 ± 0.38
Charge-flip background	1.13 ± 0.13 ± 0.24	0.74 ± 0.08 ± 0.16	-
$V\gamma$	0.75 ± 0.35 ± 0.21	2.5 ± 0.7 ± 0.7	-
Fake-lepton background	0.96 ± 0.15 ± 0.39	2.04 ± 0.22 ± 0.89	0.43 ± 0.06 ± 0.25
Total background	4.0 ± 0.4 ± 0.7	9.4 ± 0.8 ± 1.4	5.0 ± 0.3 ± 0.8
Signal + background	4.5 ± 0.4 ± 0.7	10.7 ± 0.8 ± 1.4	6.7 ± 0.3 ± 0.9
Data	0	15	6

	Validation Region	Signal	Background	Observed
$\ell\nu\ell\nu\ell\nu$	Preselection	$9.78 \pm 0.04 \pm 0.45$	$2392 \pm 7 \pm 298$	2472
	Fake-lepton	$0.15 \pm 0.01 \pm 0.02$	$15 \pm 1 \pm 10$	18
	$Z\gamma$	$0.32 \pm 0.01 \pm 0.02$	$119 \pm 3 \pm 20$	119
$\ell\nu\ell\nu jj$	Charge-flip	$0.98 \pm 0.04 \pm 0.06$	$21 \pm 1 \pm 2$	22
	WZ + 2-jets	$0.55 \pm 0.03 \pm 0.04$	$52 \pm 1 \pm 10$	56
	b-tagged	$1.00 \pm 0.05 \pm 0.07$	$69 \pm 1 \pm 23$	78
	W mass sideband	$3.35 \pm 0.08 \pm 0.43$	$48 \pm 2 \pm 6$	53
	≤ 1 jet	$1.62 \pm 0.06 \pm 0.40$	$139 \pm 3 \pm 18$	145

- Signal: MadGraph5_aMC@NLO (v5.2.2)+CT10NLO+Pythia 8.1.6 @NLO
- Also use VBFNLO at LO to generate events and cross check, and normalized to VBNFLO@NLO.
- Background: Dibosons: Sherpa (V1.4) or Powheg depending on the final states. tt+V, VVV: MadGraph5_aMC@NLO

Source of Uncertainty	$\ell\nu\ell\nu\ell\nu$ Signal [%]	$\ell\nu\ell\nu\ell\nu$ Background [%]	$\ell\nu\ell\nu jj$ Signal [%]	$\ell\nu\ell\nu jj$ Background [%]
Lepton ID, $E_{\mathrm{T}}/p_{\mathrm{T}}$ scale and resolution	1.6	1.8	2.1	3.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	1.1	1.4	0.7	1.8
b-jet identification	0.3	0.3	2.2	2.2
Jet E_{T} scale and resolution	2.3	2.8	21	15
Fake-lepton background	0	13	0	8
Charge-flip background	0	0.04	0	2.2
Luminosity	1.9	1.6	1.9	1.4
Pile-up estimate	1.1	0.6	0.6	1.6
Trigger efficiency	0.1	0.1	0.1	0.01
Normalization factor	3.8	8	6.0	13
Statistical	1.2	3.2	2.7	5.1